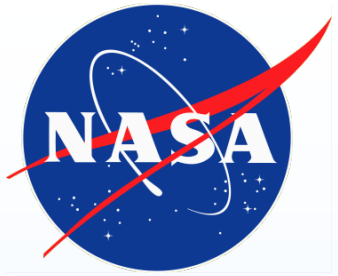


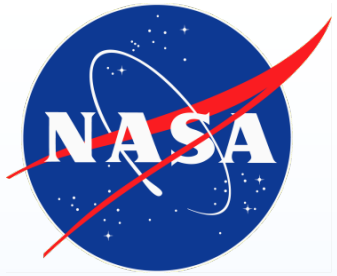
Destructive Single-Event Effects in Diodes

Megan C. Casey[1], Jean-Marie Lauenstein[1],
Michael J. Campola[1], Edward P. Wilcox[2], Anthony M. Phan[2],
and Kenneth A. LaBel[1]

[1]NASA Goddard Space Flight Center
[2]ASRC Federal Space and Defense, Inc. (AS&D, Inc.)

To be presented by Megan C. Casey at the NASA Electronics Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 26-29, 2017.

Acronyms



- DUT – Device Under Test
- EDS – Energy Dispersive X-Ray Spectroscopy
- ETW – Electronics Technology Workshop
- GSFC – Goddard Space Flight Center
- I_F – Forward Current
- I_R – Reverse Current
- IR – infrared
- LET – Linear Energy Transfer
- NEPP – NASA Electronics Parts and Packaging
- RF – Radio Frequency
- SBD – Super Barrier Diode
- SEE – Single-Event Effects
- V_R – Reverse Voltage
- V_F – Forward Voltage

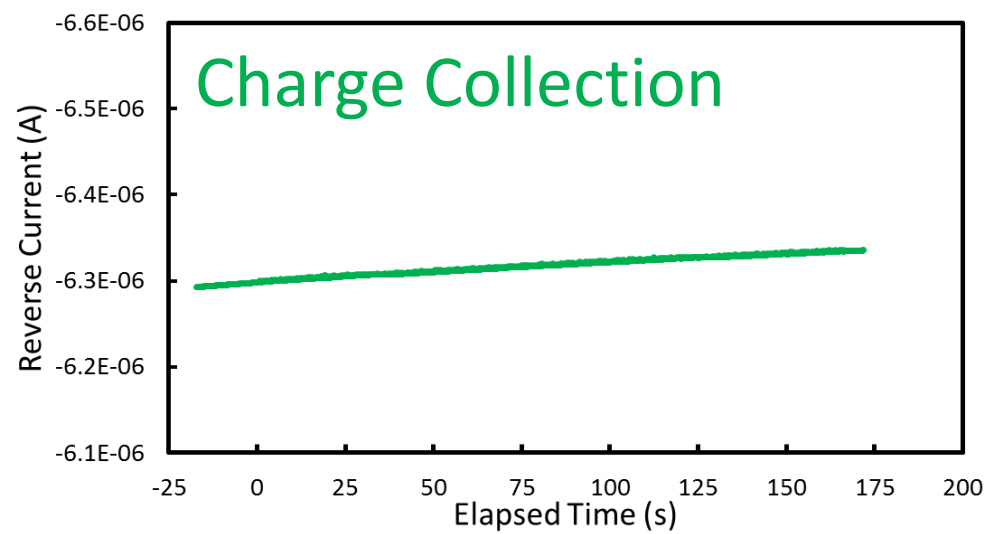
Background and Summary of Previous Results

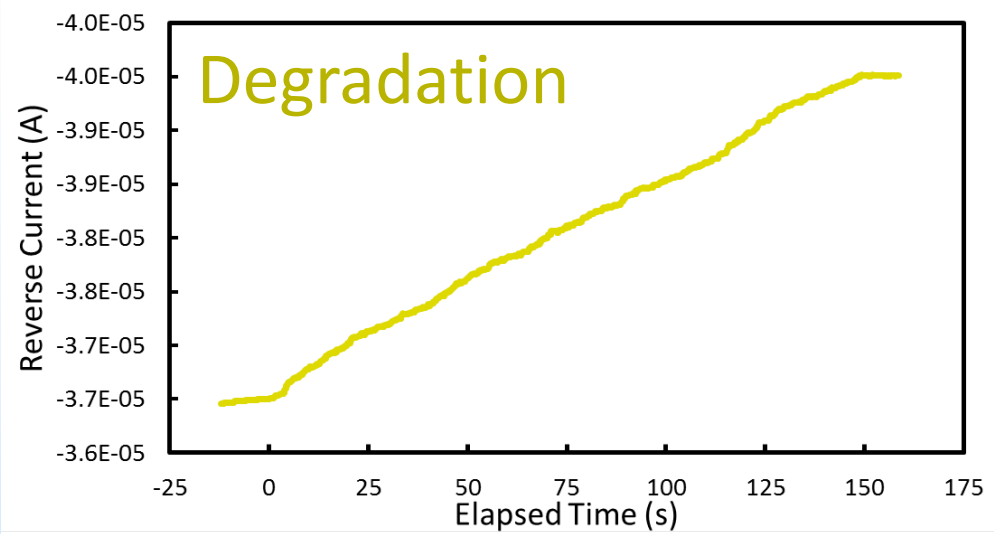
Introduction

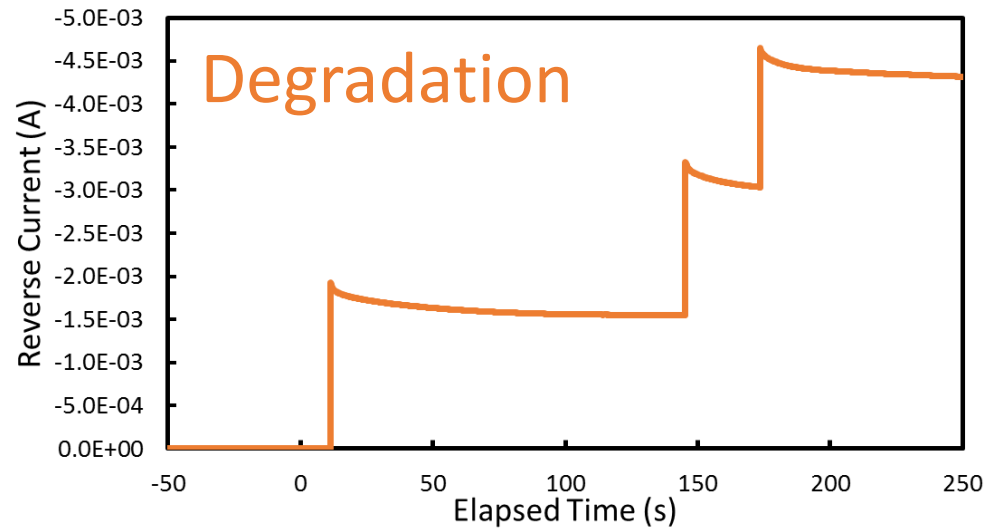
- Since 2011, GSFC has been investigating destructive SEEs in Schottky diodes
  - We have recommended a 50% V_R derating for operation in heavy-ion environments

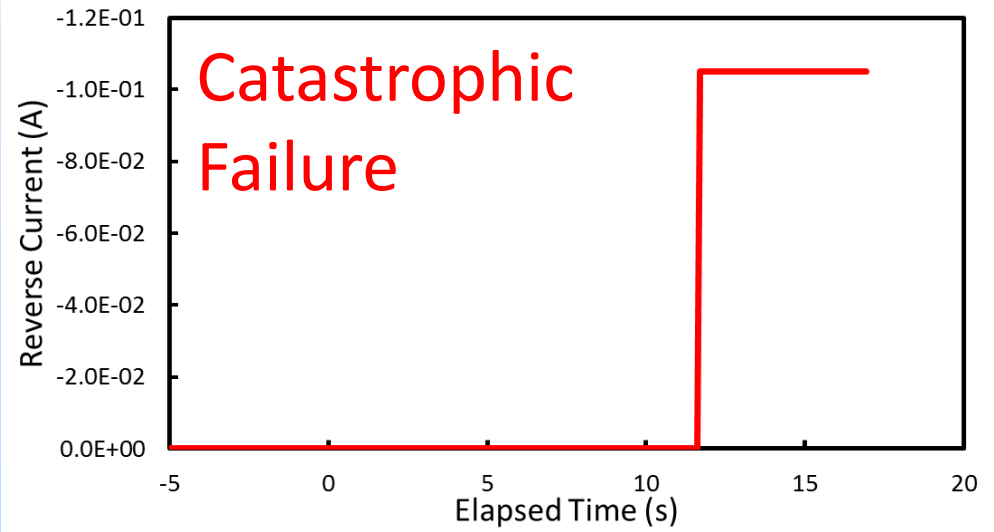
- During this investigation, several super barrier diodes were also irradiated and experienced failures identical to the Schottky diodes that were tested
  - In retrospect, this is not totally unexpected as SBDs also have a Schottky junction, but also employs an insulating layer between the metal and semiconductor material
  - However, this led us to question whether the failure mechanism is limited to diodes with Schottky junctions or if it exists in other diode types as well

Background – Observed Radiation Responses

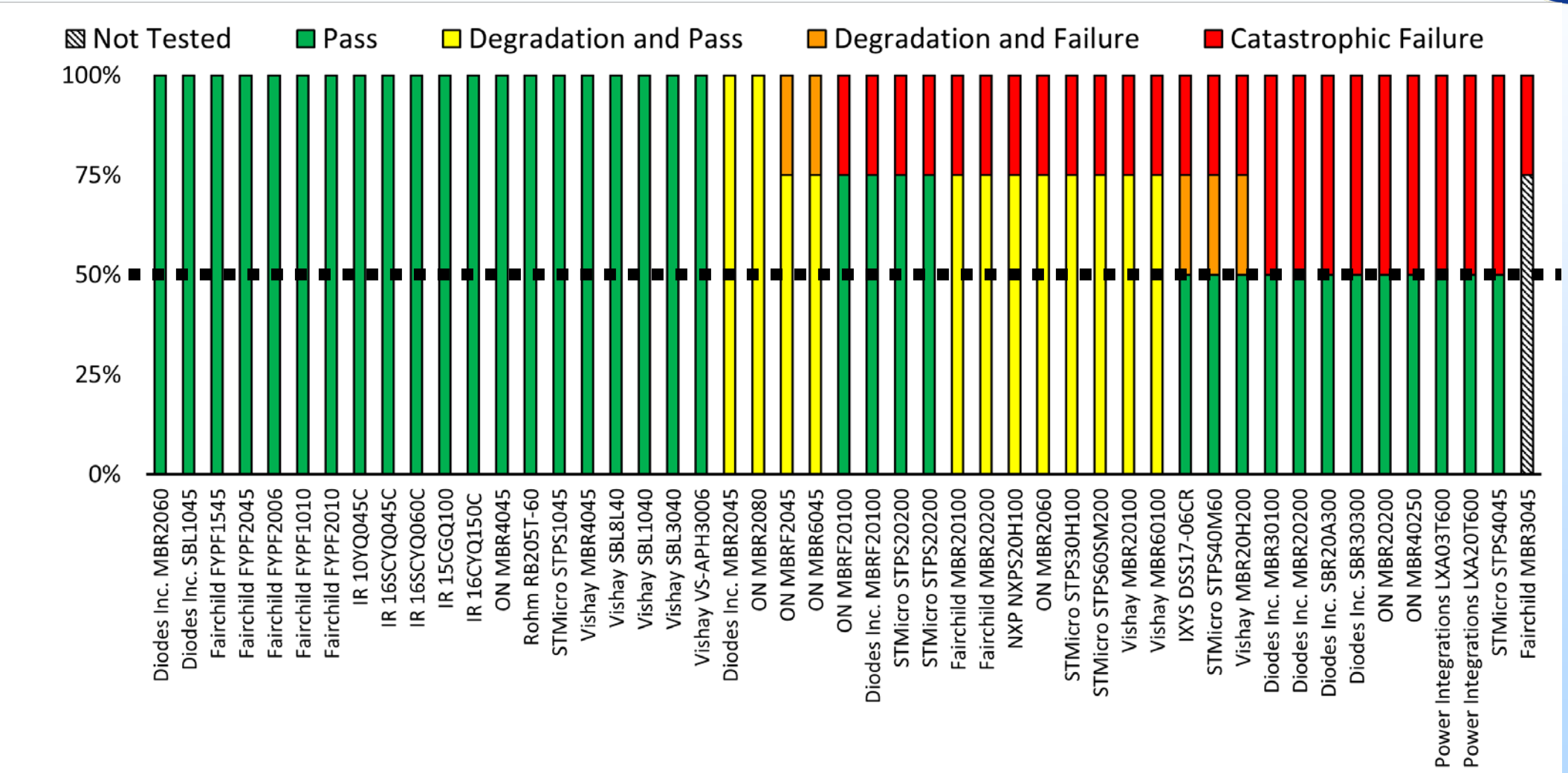






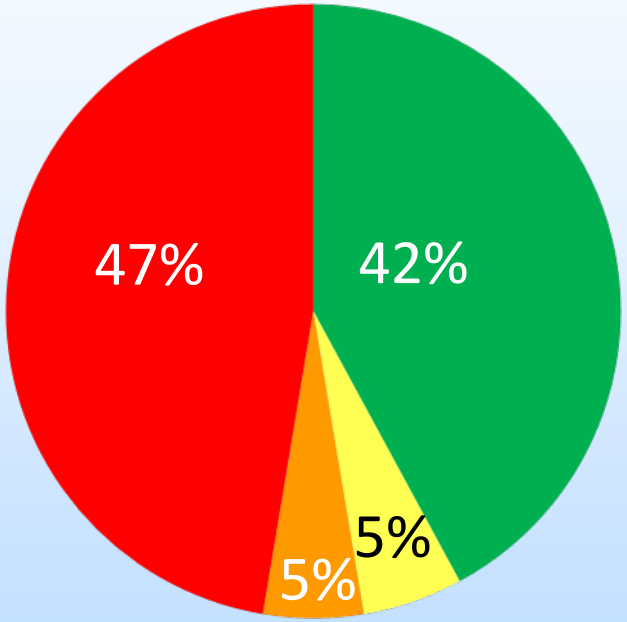


Background – Schottky Diode Results

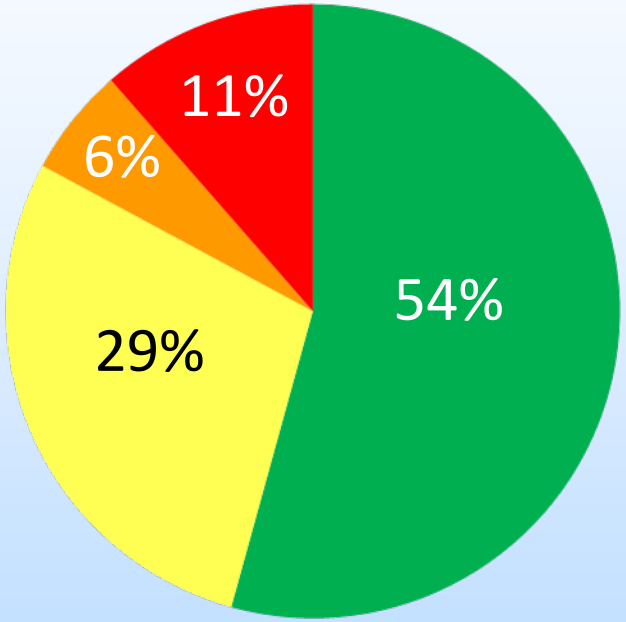


Background – Schottky Diode Results

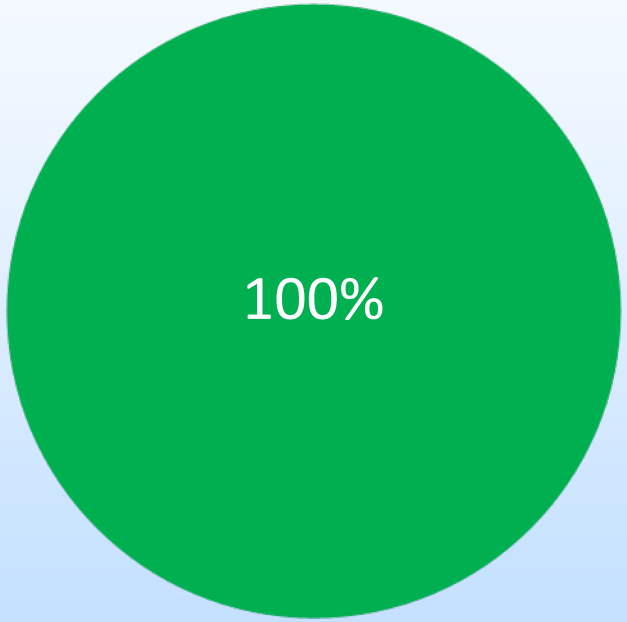
100% of Reverse Voltage



75% of Reverse Voltage



50% of Reverse Voltage



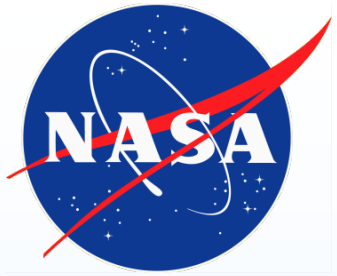
By derating to 50% of the reverse voltage, all failures are eliminated for the parts tested

Current Results – Other Diode Types

Parts Tested

- 30 diodes from 10 manufacturers
- 5 diode types: avalanche, RF PiN, super barrier, switching, and Zener
- Reverse voltages range from 35 V to 200 V
- Forward currents (per diode) from 2 mA to 10 A

Test Facilities and Technique



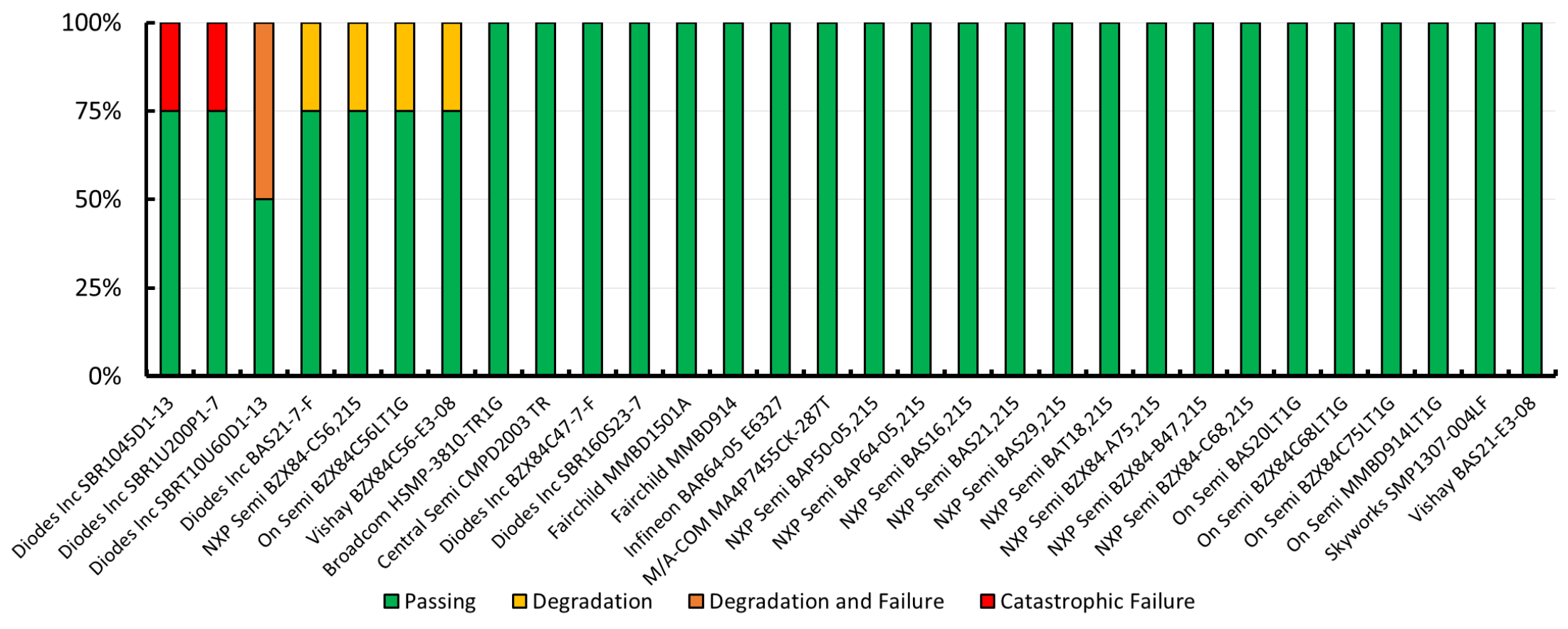
- All parts were tested at LBNL's 88-inch cyclotron with 1233 MeV Xe (LET = 58.8 MeV-cm^2/mg)
- All diodes were irradiated under reverse bias and at room temperature
- After each beam run, V_F, V_R, I_F and I_R were measured
- Because a 50% derating has been found to be sufficient for Schottky diodes, that was the initial test voltage
- A minimum of 3 DUTs per part type were tested

Diodes Tested

Diode Type	Manufacturer	Part Number	Reverse Voltage	Forward Current
Avalanche	NXP Semi	BAS29,215	90 V	200 mA
Super Barrier	Diodes Inc	SBR1U200P1-7	200 V	1 A
Super Barrier	Diodes Inc	SBR1045D1-13	45 V	10 A
Super Barrier	Diodes Inc	SBR160S23-7	60 V	900 mA
Super Barrier	Diodes Inc	SBRT10U60D1-13	60 V	10 A
Zener	Diodes Inc	BZX84C47-7-F	47 V	10 mA
Zener	NXP Semi	BZX84-B47,215	47 V	10 mA
Zener	NXP Semi	BZX84-C56,215	56 V	10 mA
Zener	NXP Semi	BZX84-C68,215	68 V	10 mA
Zener	NXP Semi	BZX84-A75,215	75 V	10 mA
Zener	On Semi	BZX84C56LT1G	56 V	10 mA
Zener	On Semi	BZX84C68LT1G	68 V	10 mA
Zener	On Semi	BZX84C75LT1G	75 V	10 mA
Zener	Vishay	BZX84C56-E3-08	56 V	2 mA

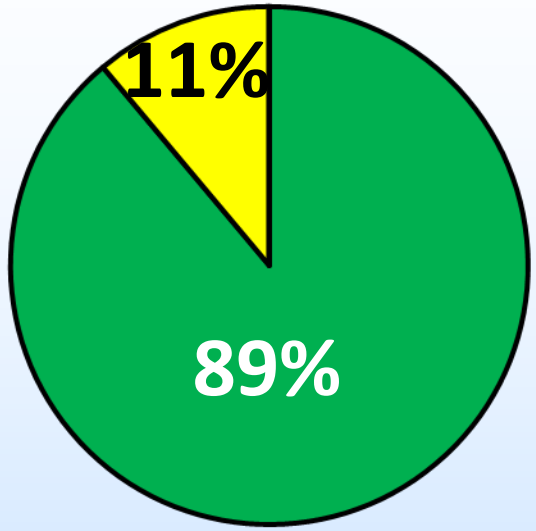
Diode Type	Manufacturer	Part Number	Reverse Voltage	Forward Current
PiN	Broadcom	HSMP-3810-TR1G	100 V	1 A
PiN	Infineon	BAR64-05 E6327	150 V	100 mA
PiN	M/A-COM	MA4P7455CK-287T	100 V	150 mA
PiN	NXP Semi	BAP64-05,215	175 V	100 mA
PiN	NXP Semi	BAT18,215	35 V	100 mA
PiN	NXP Semi	BAP50-05,215	50 V	50 mA
PiN	Skyworks	SMP1307-004LF	200 V	100 mA
Switching	Central Semi	CMPD2003 TR	200 V	200 mA
Switching	Diodes Inc	BAS21-7-F	200 V	200 mA
Switching	Fairchild	MMBD914	100 V	200 mA
Switching	Fairchild	MMBD1501A	200 V	200 mA
Switching	NXP Semi	BAS16,215	100 V	215 mA
Switching	NXP Semi	BAS21,215	200 V	200 mA
Switching	On Semi	MMBD914LT1G	100 V	200 mA
Switching	On Semi	BAS20LT1G	200 V	200 mA
Switching	Vishay	BAS21-E3-08	200 V	200 mA

Results

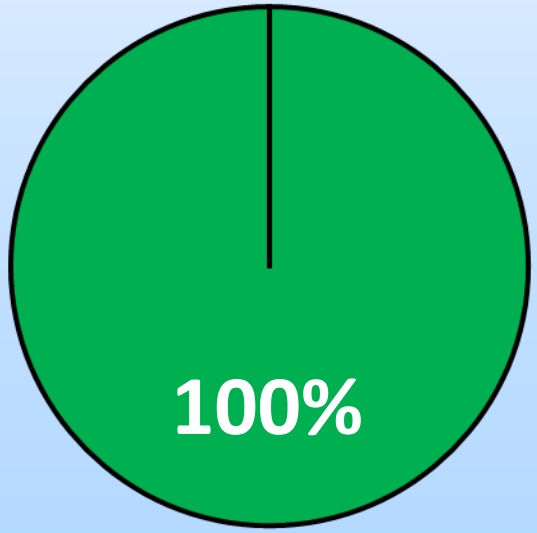

100%
75%
50%
25%
0%
Diodes Inc SBR1045D1-13
Diodes Inc SBR1U200P1-7
Diodes Inc SBRT10U60D1-13
Diodes Inc BAS21-7-F
NXP Semi BZX84-C56,215
On Semi BZX84C56LT1G
Vishay BZX84C56-E3-08
Broadcom HSMP-3810-TR1G
Central Semi CMPD2003 TR
Diodes Inc BZX84C47-7-F
Diodes Inc SBR160S23-7
Fairchild MMBD1501A
Fairchild MMBD914
Infineon BAR64-05 E6327
M/A-COM MA4P7455CK-287T
NXP Semi BAP50-05,215
NXP Semi BAP64-05,215
NXP Semi BAS16,215
NXP Semi BAS21,215
NXP Semi BAS29,215
NXP Semi BAT18,215
NXP Semi BZX84-A75,215
NXP Semi BZX84-B47,215
NXP Semi BZX84-C68,215
On Semi BAS20LT1G
On Semi BZX84C68LT1G
On Semi BZX84C75LT1G
On Semi MMBD914LT1G
Skyworks SMP1307-004LF
Vishay BAS21-E3-08
Passing
Degradation
Degradation and Failure
Catastrophic Failure

Results – RF Switching Diodes

Manufacturer	Part Number	Reverse Voltage	Forward Current
Fairchild	MMBD914	100 V	200 mA
NXP Semi	BAS16,215	100 V	215 mA
On Semi	MMBD914LT1G	100 V	200 mA
Diodes Inc	BAS21-7-F	200 V	200 mA
Central Semi	CMPD2003 TR	200 V	200 mA
Fairchild	MMBD1501A	200 V	200 mA
NXP Semi	BAS21,215	200 V	200 mA
On Semi	BAS20LT1G	200 V	200 mA
Vishay	BAS21-E3-08	200 V	200 mA



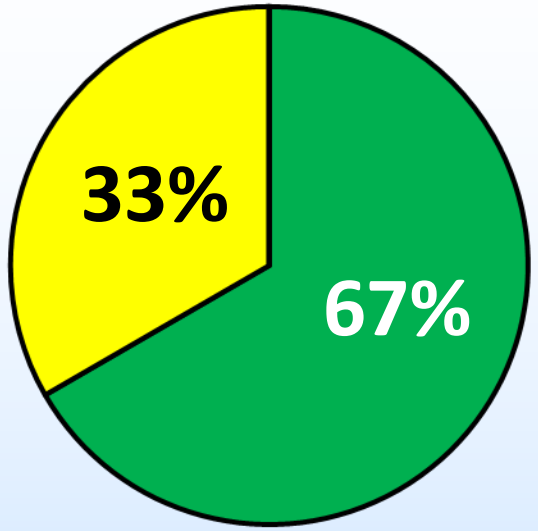
100% of Rated Reverse Voltage



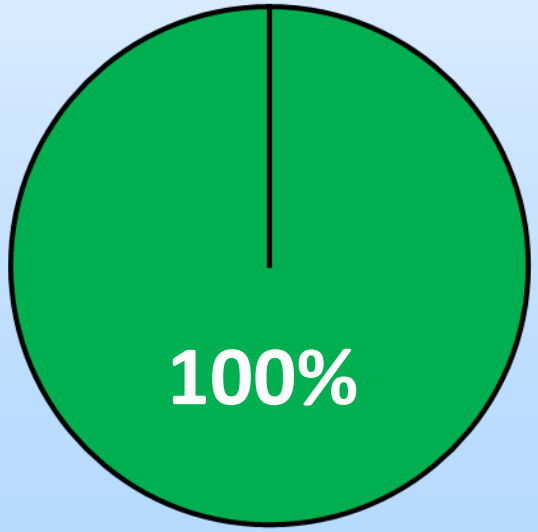
75% of Rated Reverse Voltage

Results – Zener Diodes

Manufacturer	Part Number	Zener Voltage	Forward Current
Diodes Inc	BZX84C47-7-F	47 V	10 mA
NXP Semi	BZX84-B47,215	47 V	10 mA
NXP Semi	BZX84-C56,215	56 V	10 mA
On Semi	BZX84C56LT1G	56 V	10 mA
Vishay	BZX84C56-E3-08	56 V	2 mA
NXP Semi	BZX84-C68,215	68 V	10 mA
On Semi	BZX84C68LT1G	68 V	10 mA
NXP Semi	BZX84-A75,215	75 V	10 mA
On Semi	BZX84C75LT1G	75 V	10 mA



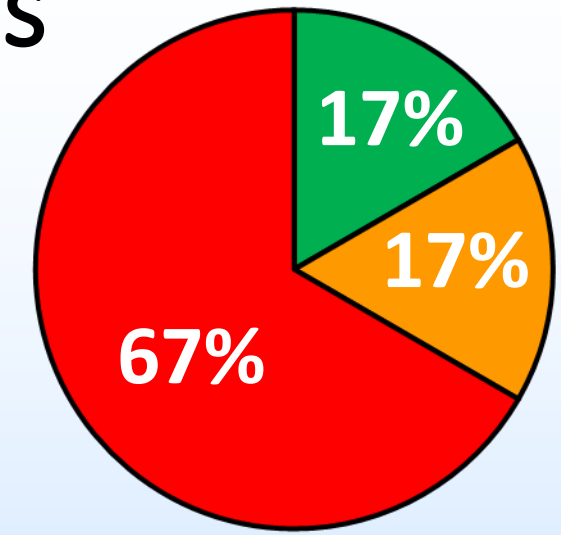
100% of Rated Reverse Voltage



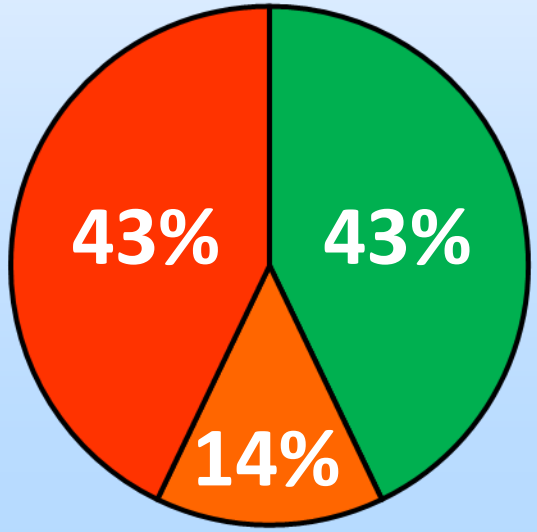
75% of Rated Reverse Voltage

Results – Super Barrier Diodes

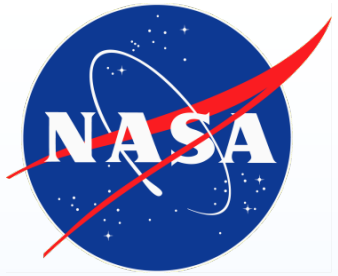
Manufacturer	Part Number	Reverse Voltage	Forward Current
Diodes Inc	SBR1045D1-13	45 V	10 A
Diodes Inc	SBRT10U60D1-13	60 V	10 A
Diodes Inc	SBR160S23-7	60 V	900 mA
Diodes Inc	SBR1U200P1-7	200 V	1 A
Diodes Inc	SBR20A300	300 V	10 A
Diodes Inc	SBR30300	300 V	15 A



100% of Rated Reverse Voltage

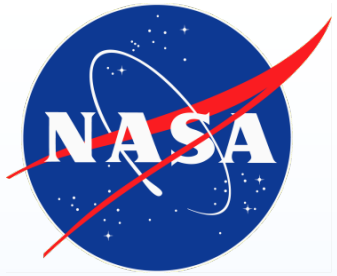


75% of Rated Reverse Voltage

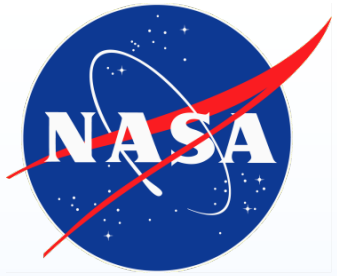


Recap of 2016 ETW Presentation

2016 NEPP ETW



- Last year, I presented a case study of a 1N6843 from two different manufacturers being used on a flight project
  - The reverse voltage is 100 V and forward current is 10 A
  - Normal application reverse voltage is ~60 V and worst case application reverse voltage is ~82 V
  - There are currently no mission **radiation** requirements for diodes; so destructive SEEs requirements were used for this testing
- The irradiated parts experienced all four radiation responses
  - By conducting failure analysis on these DUTs, we are hoping to derive additional information about the failure mechanisms

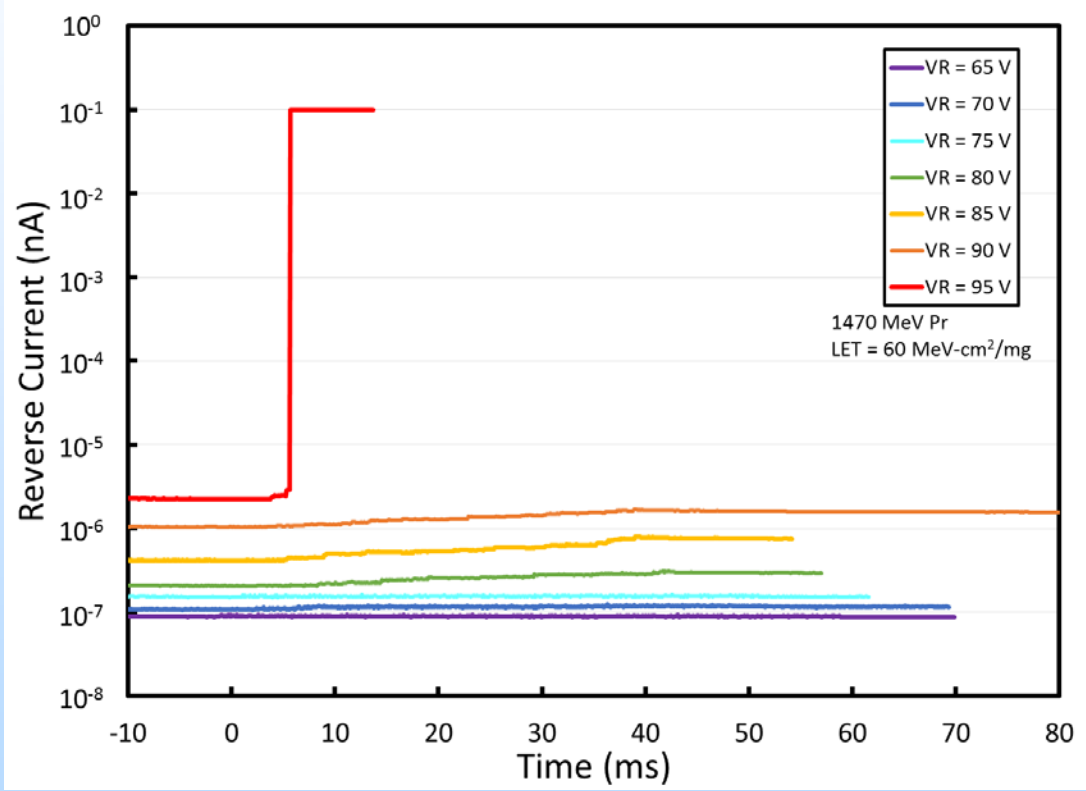


Failure Analysis

Catastrophic Failure

Power Supply Currents

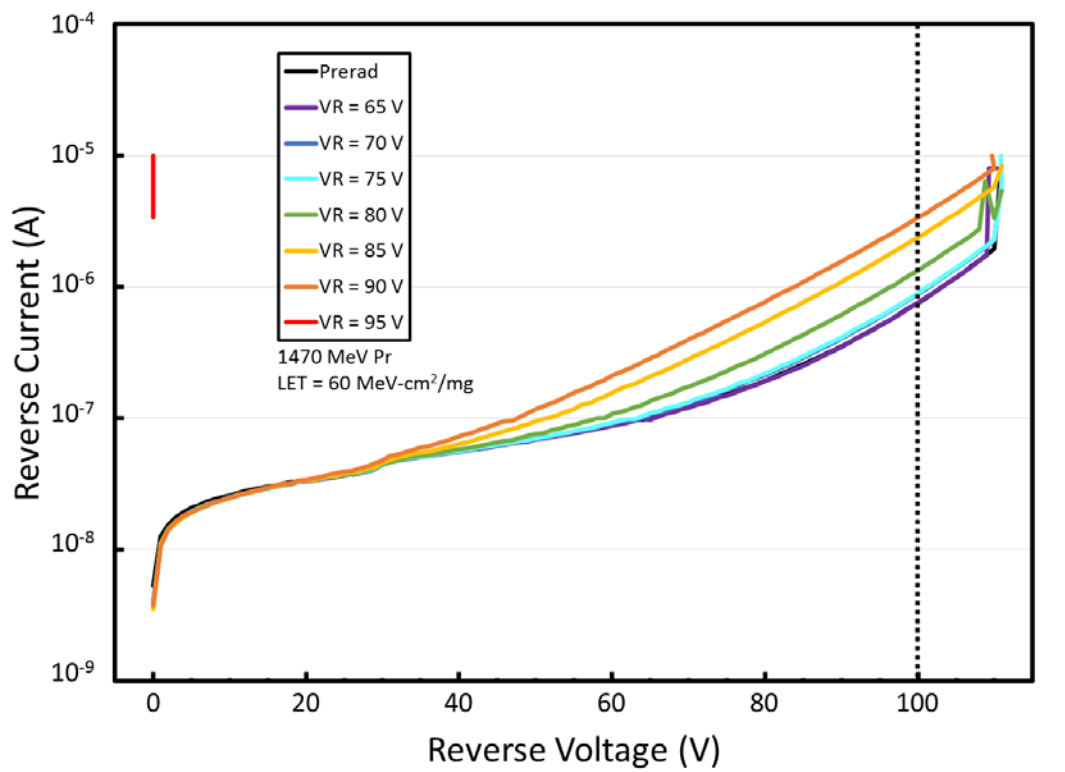
- SN5 was irradiated with 1470 MeV Pr (LET = 60 MeV-cm^2/mg) in 5 V steps starting at 50 V (50% of the rated reverse voltage)
- Only charge collection was observed up to the 65-V irradiation
- When biased at 70 V, small increases in the reverse current were observed during the beam run
  - Post-irradiation electrical parameter measurements all remained within specification
  - Increases in reverse current were on the order of 100 nA
- At 95 V, the increase in reverse current was 100s of nA



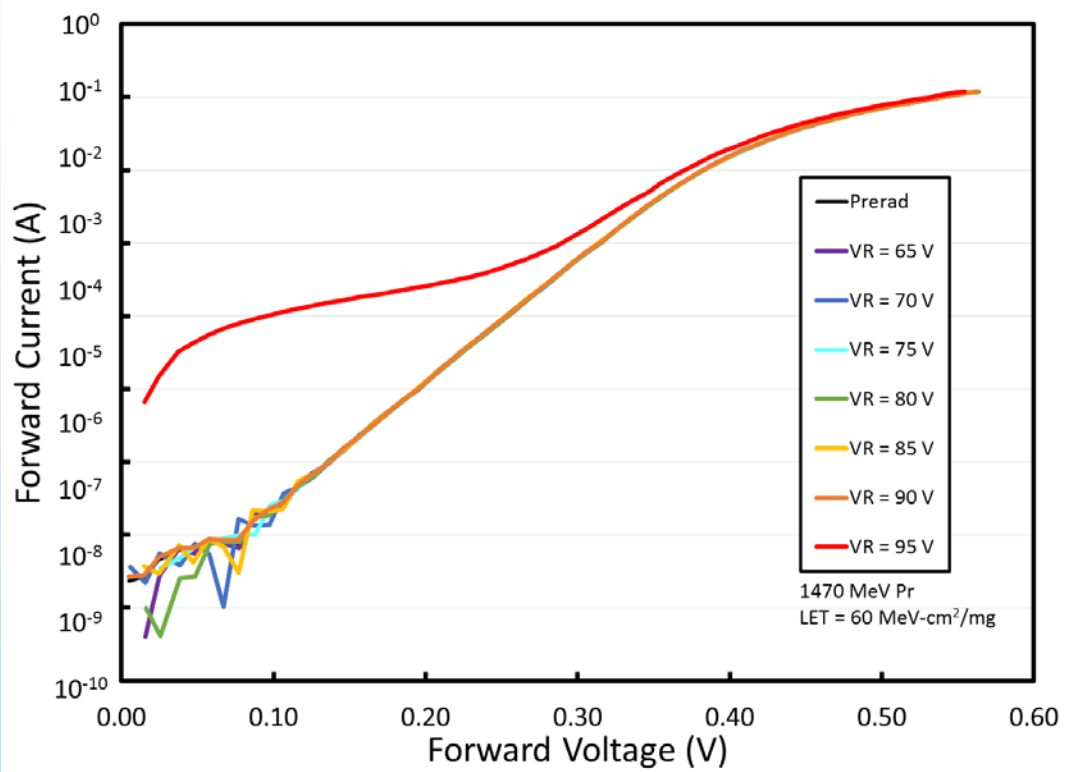
Catastrophic Failure

Post-Irradiation Electrical Measurements

Reverse Current vs. Reverse Voltage



Forward Current vs. Forward Voltage

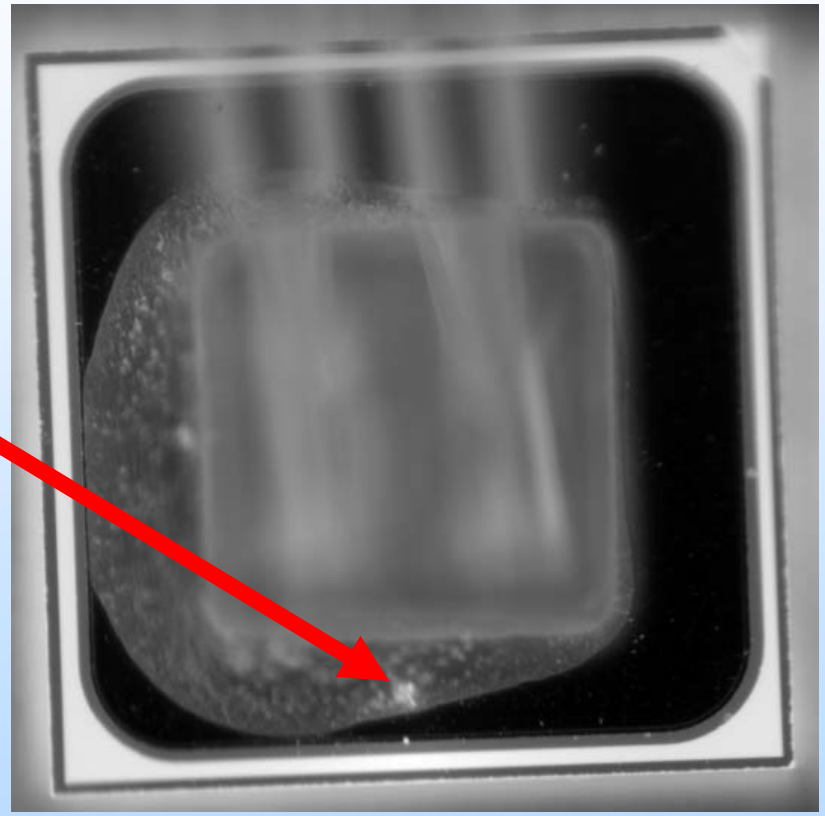


Part was degrading until after the 95-V run, and then I_R exceeded 10 µA at less than 1 V

Catastrophic Failure

Infrared Imaging of DUT

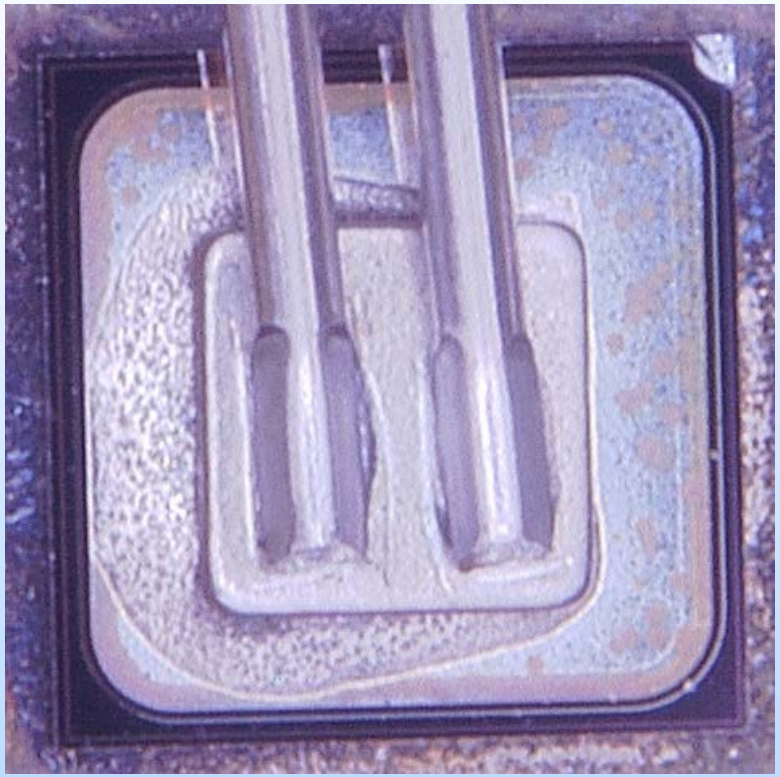
- Diode was examined using an IR camera and pictures were taken with a small voltage applied
  - Bright white spot just below the wirebond contact is the location of the failure
- Low-magnitude and high-magnitude optical images of the surface of the DUT did not show anything unusual at the location identified in the IR image



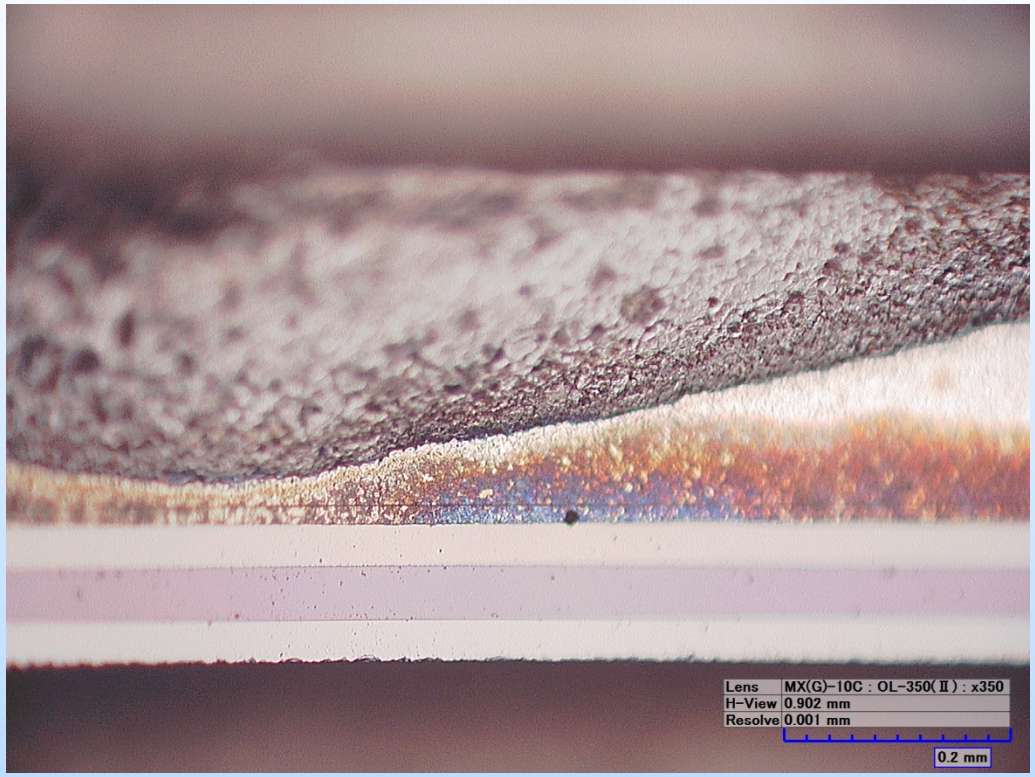
Catastrophic Failure

Optical Images of DUT

Low-Magnification



High-Magnification

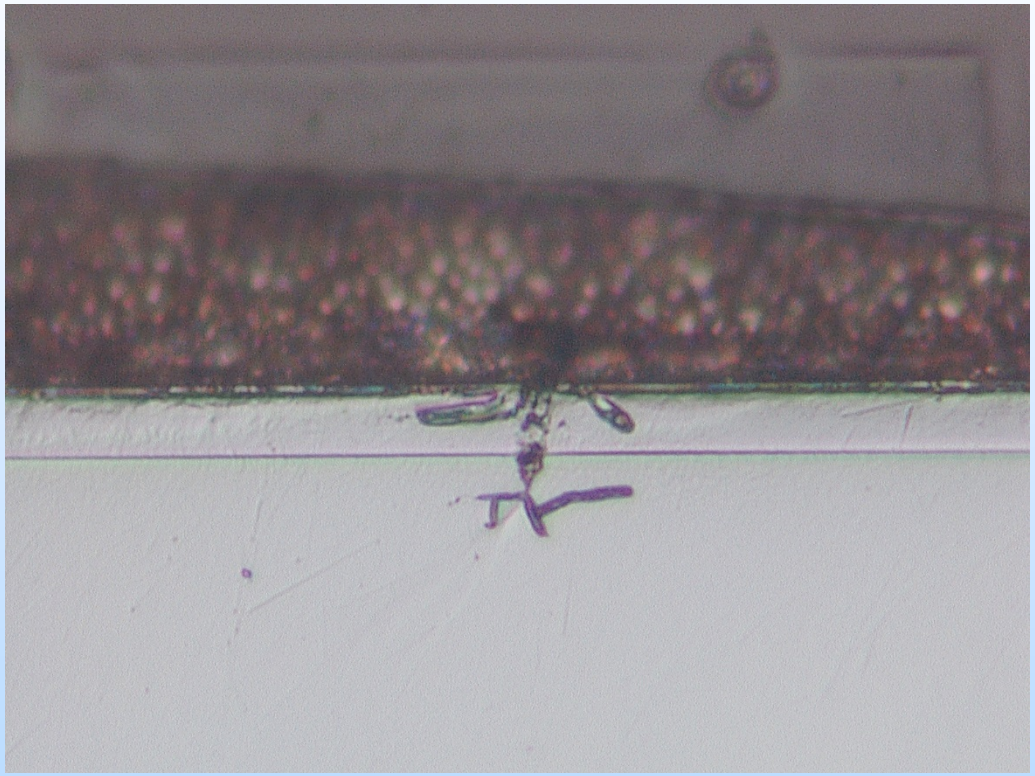


Failure location is not visible in optical images

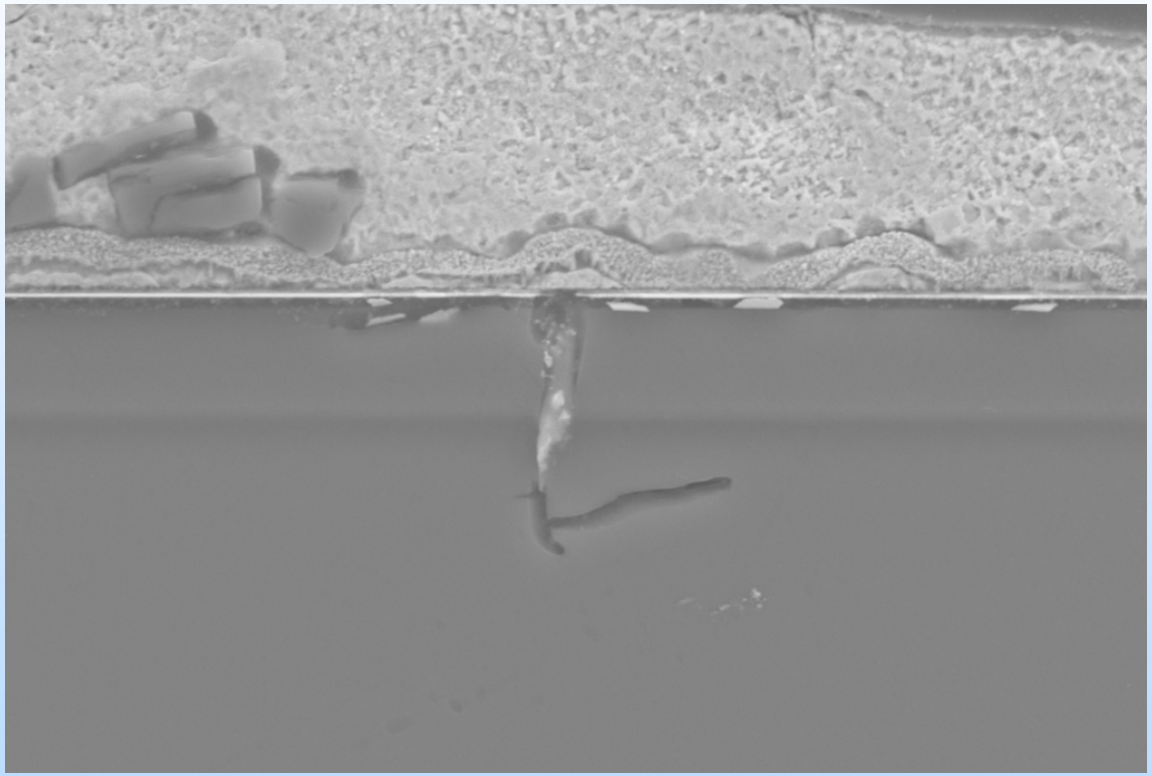
Catastrophic Failure

Cross-Section at Failure Location

High-Magnification Optical Image



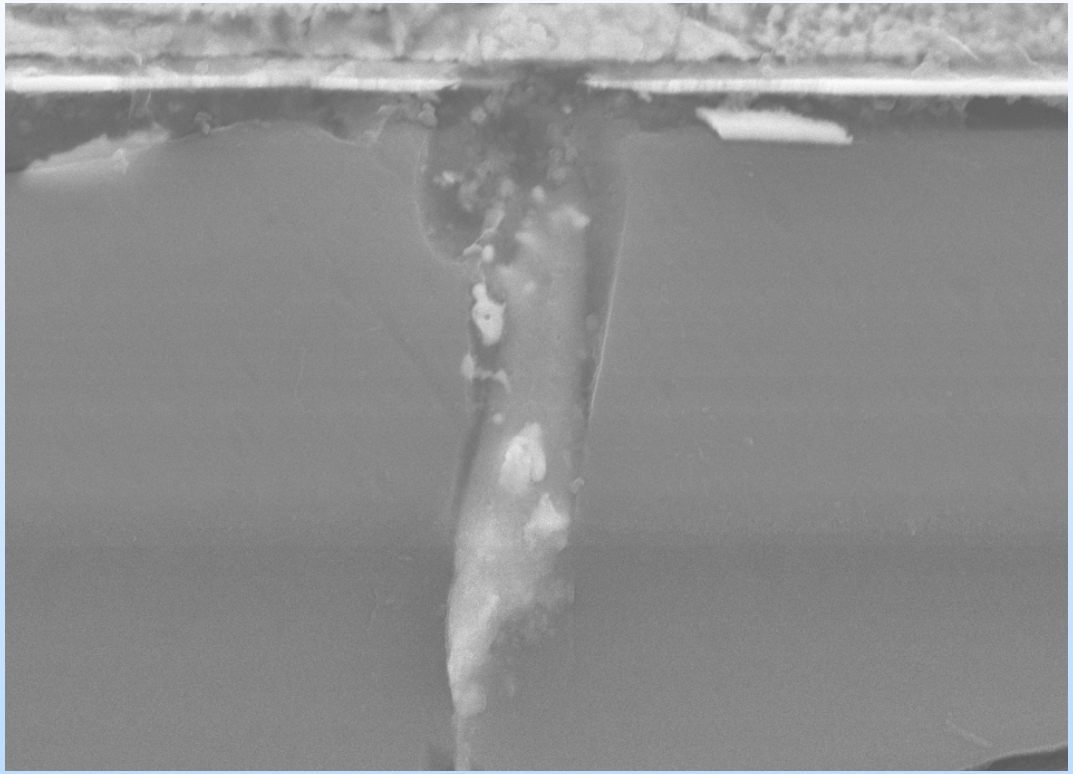
Scanning Electron Microscope Image



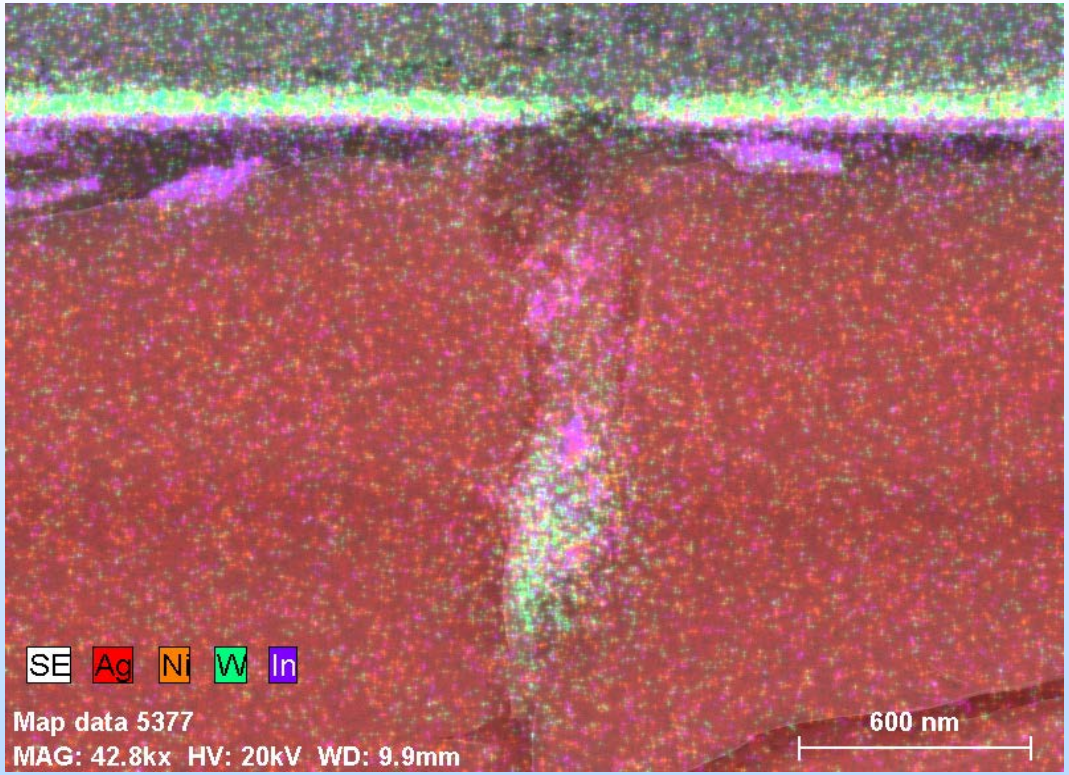
Catastrophic Failure

Energy Dispersive X-Ray Spectroscopy

Magnification of SEM Image



Map of Ag, Ni, W, and In

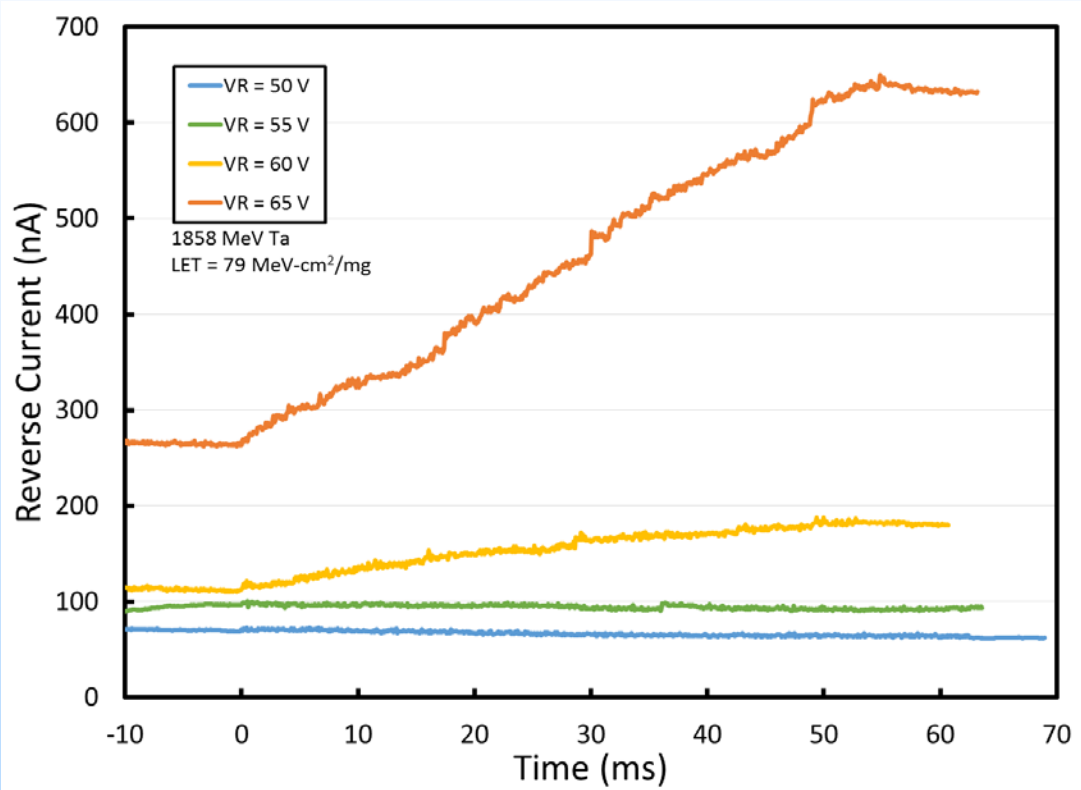


Metal has clearly displaced from Schottky junction into void formed from high current

Degradation and Failure

Power Supply Currents

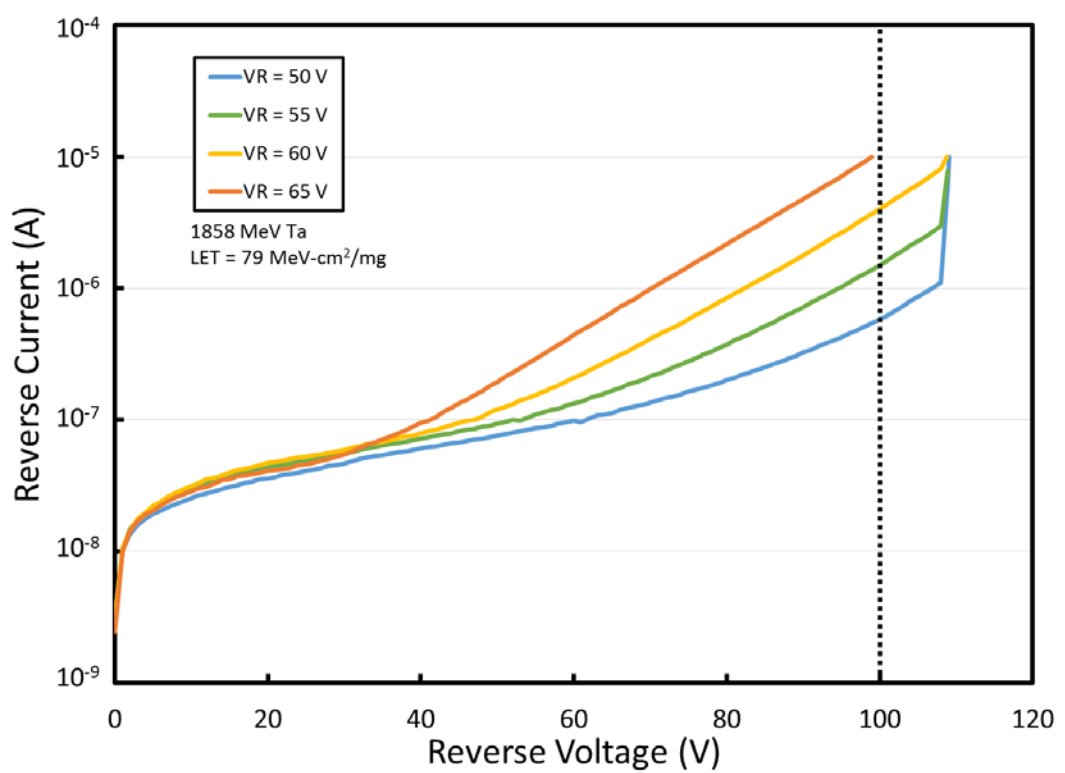
- SN2 was irradiated with 1858 MeV Ta (LET = 79 MeV-cm^2/mg) in 5 V steps starting at 50 V (50% of the rated reverse voltage)
- Only charge collection was observed up to the 55-V irradiation
- When biased at 60 V, a ~60 nA increase in I_R was observed
  - All post-irradiation parameter measurements remained within specification
- At 65 V, however, DUT experienced 100s of nA in degradation and post-irradiation I_R measurement was out of specification



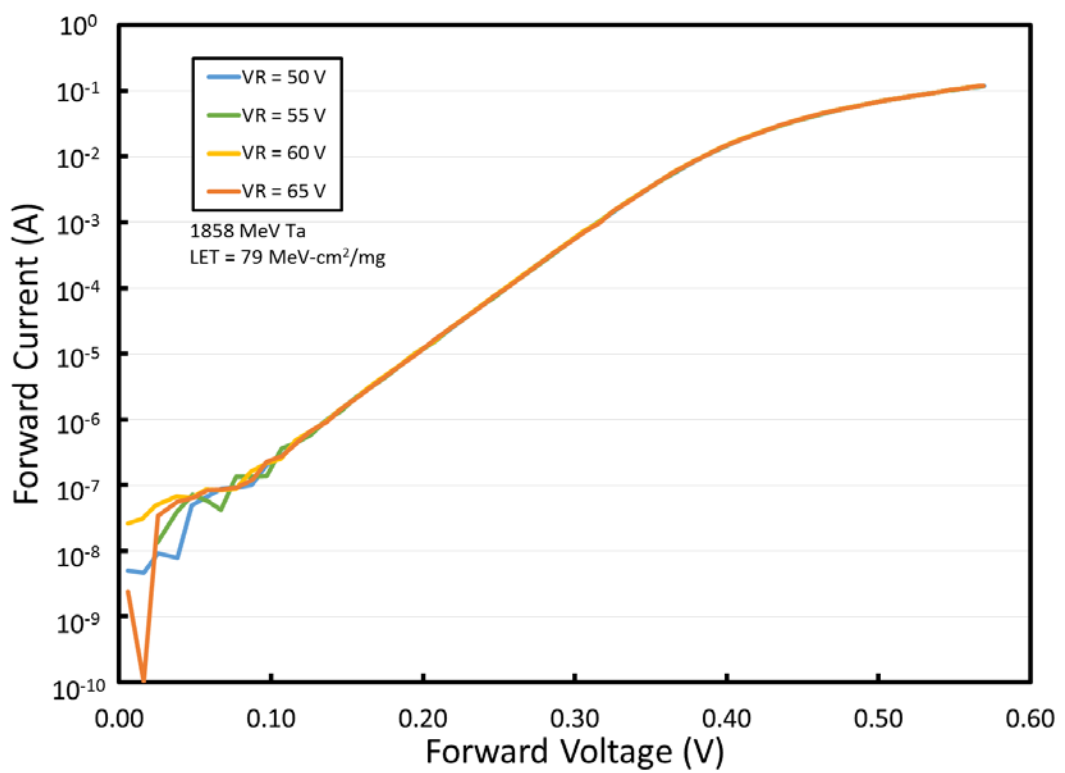
Degradation and Failure

Post-Irradiation Electrical Measurements

Reverse Current vs. Reverse Voltage



Forward Current vs. Forward Voltage

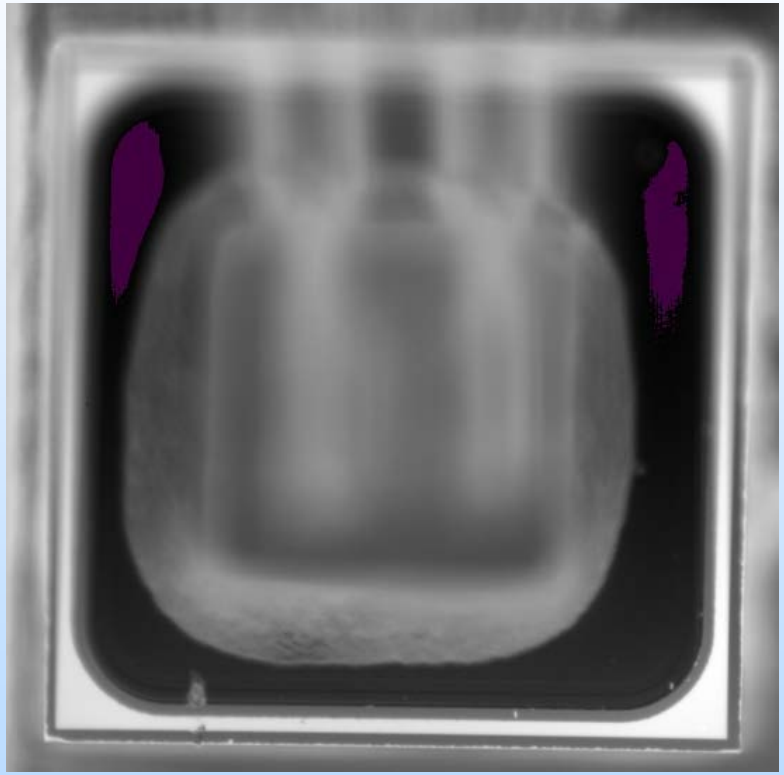


No significant changes were observed in the I_F-V_F curves, but I_R exceeded specification at less than 100 V

Degradation and Failure

Infrared Imaging of DUT

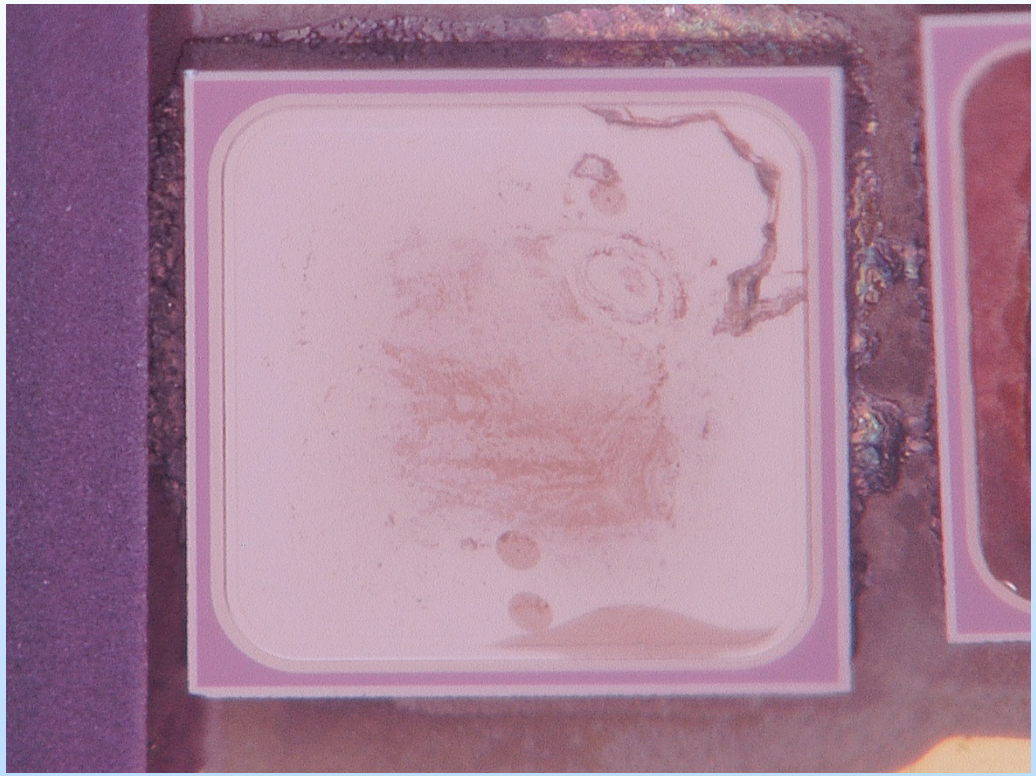
- Diode was examined using an IR camera and pictures were taken with a small voltage applied
  - No failure locations could be identified
- Low-magnitude and high-magnitude optical images of the surface of the DUT also did not show anything unusual
- Because no failure locations were identified, a different technique had to be used
  - A series of chemical etches were used to remove the contact pad, solder connection, and Schottky barrier metal



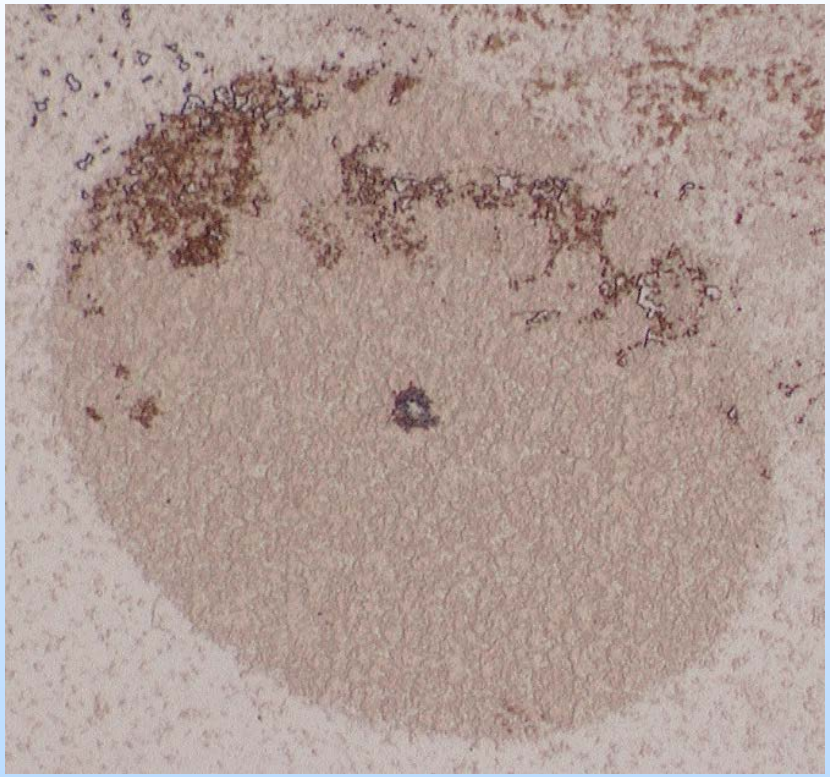
Degradation and Failure

Optical Images of DUT

Low-Magnification



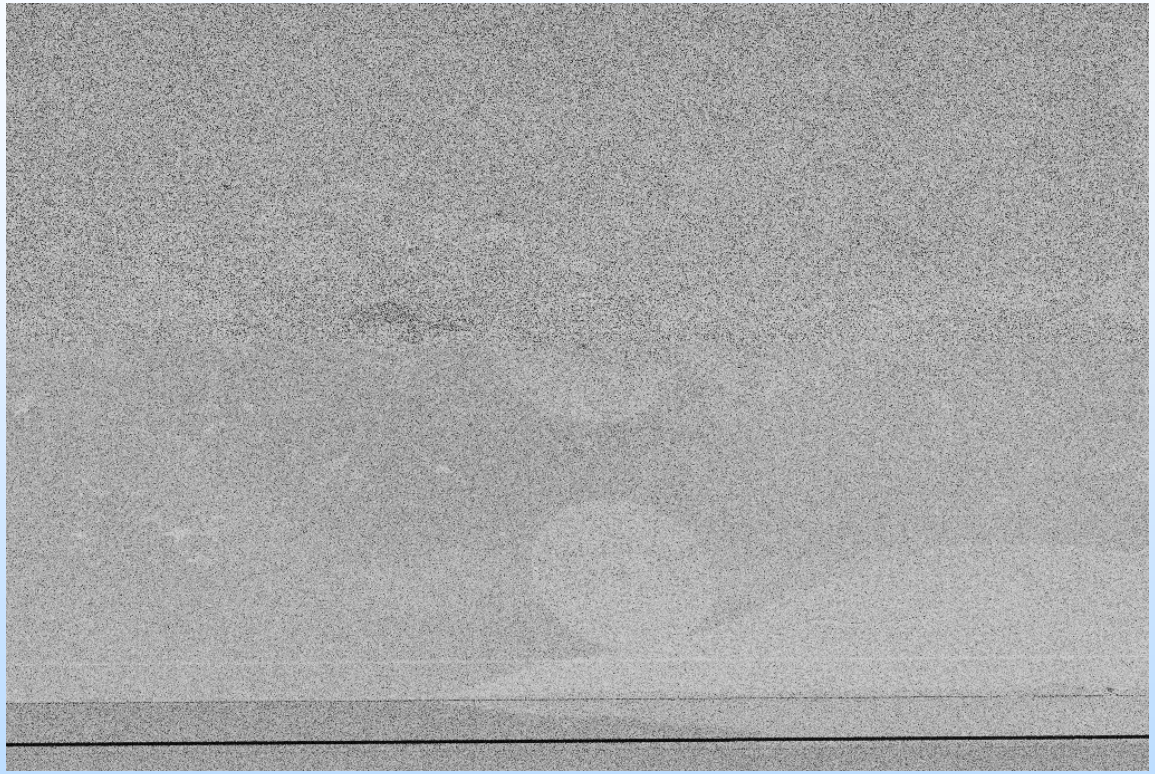
High-Magnification



After chemical etches, a few small discolored locations were identified with displaced silicon at the center

Degradation and Failure

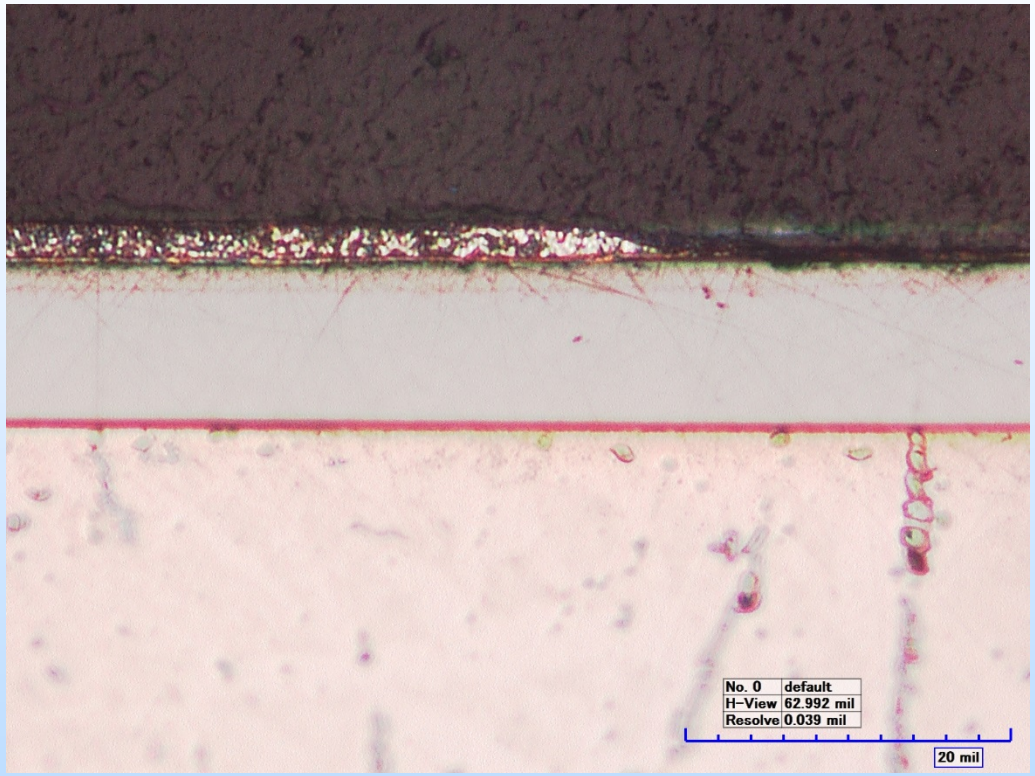
Scanning Electron Microscope Images



Displaced silicon ball was unable to be removed from surface of the diode

Degradation and Failure

Cross-Section at Displaced Silicon Location

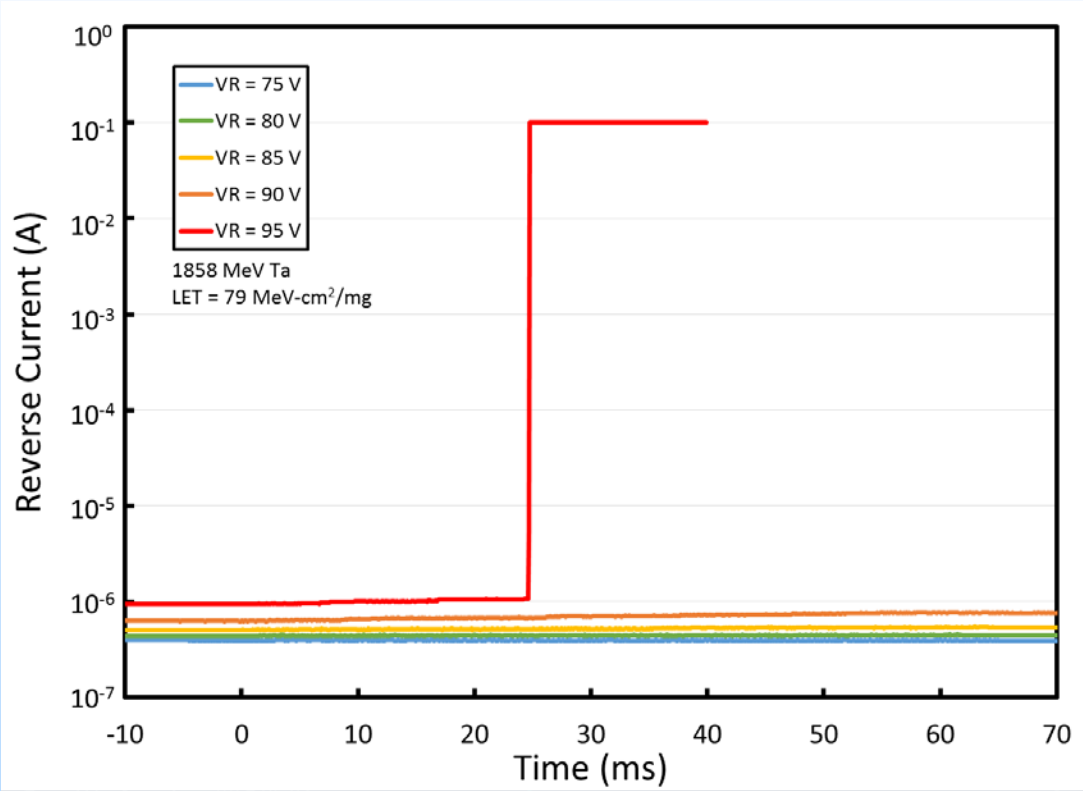


There is no damage structure visible in the damaged diode cross-section

Catastrophic Failure

Power Supply Currents

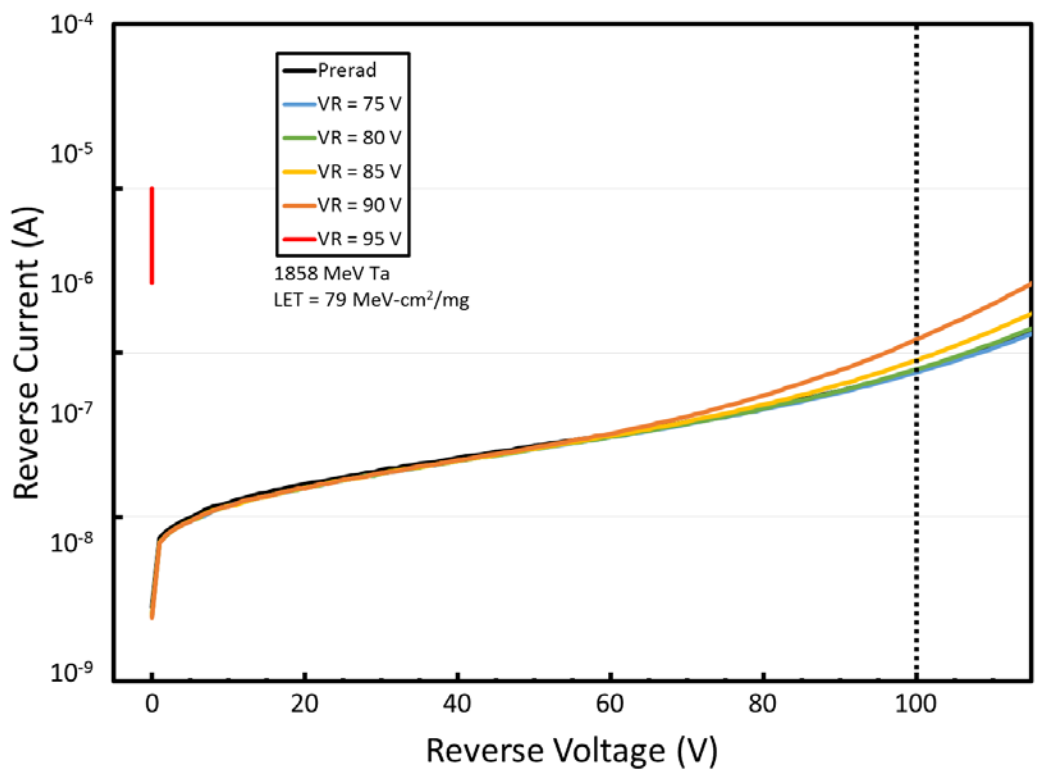
- SN7 was irradiated with 1858 MeV Ta (LET = 79 MeV-cm^2/mg) in 5 V steps starting at 75 V
- Only charge collection was observed up to the 85-V irradiation
- When biased at 90 V, a ~140 nA increase in I_R was observed
  - All post-irradiation parameter measurements remained within specification
- At 95 V, the current reached the maximum 100 mA allowed by the power supply, and the anode and cathode were shorted together



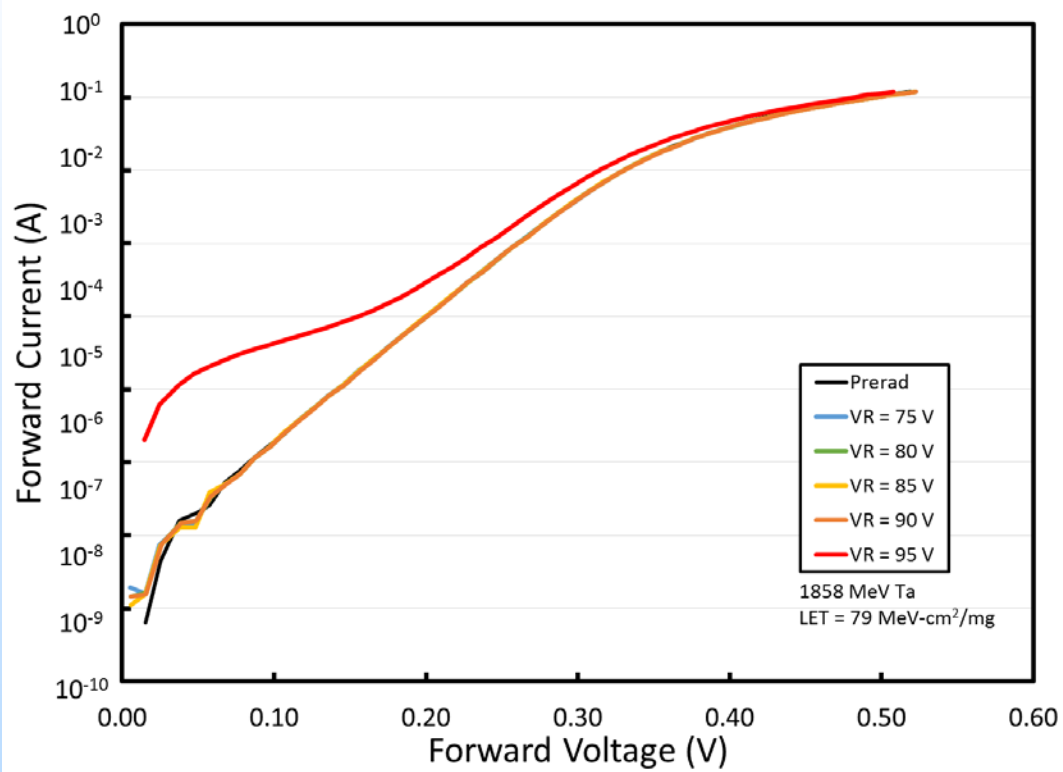
Catastrophic Failure

Post-Irradiation Electrical Measurements

Reverse Current vs. Reverse Voltage



Forward Current vs. Forward Voltage

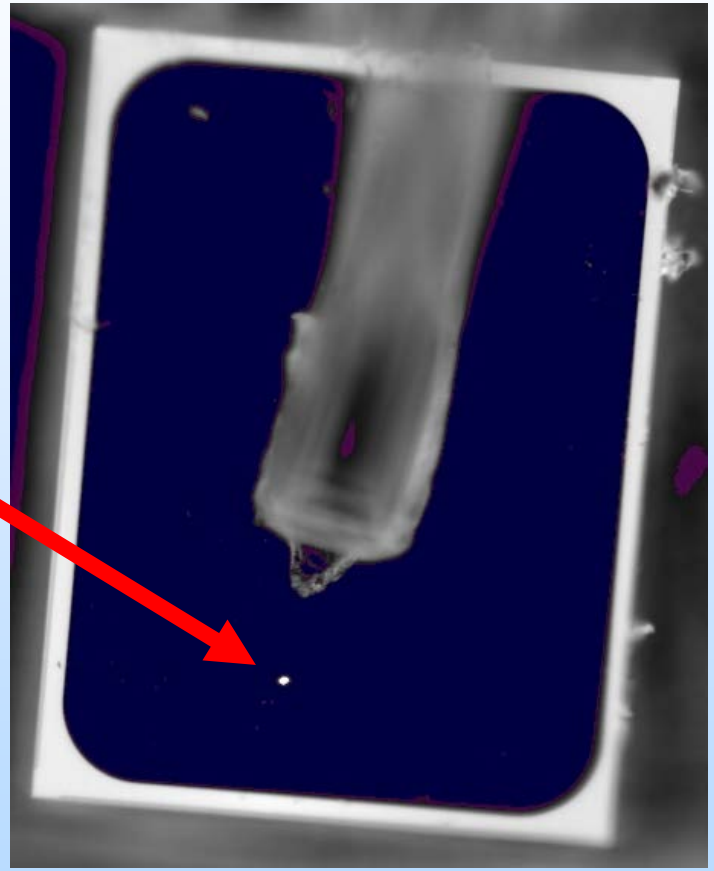


Almost no change was observed in the I_R-V_R or I_F-V_F plots until the 95-V irradiation, and then I_R exceeded 10 µA at less than 1 V

Catastrophic Failure

Infrared Imaging of DUT

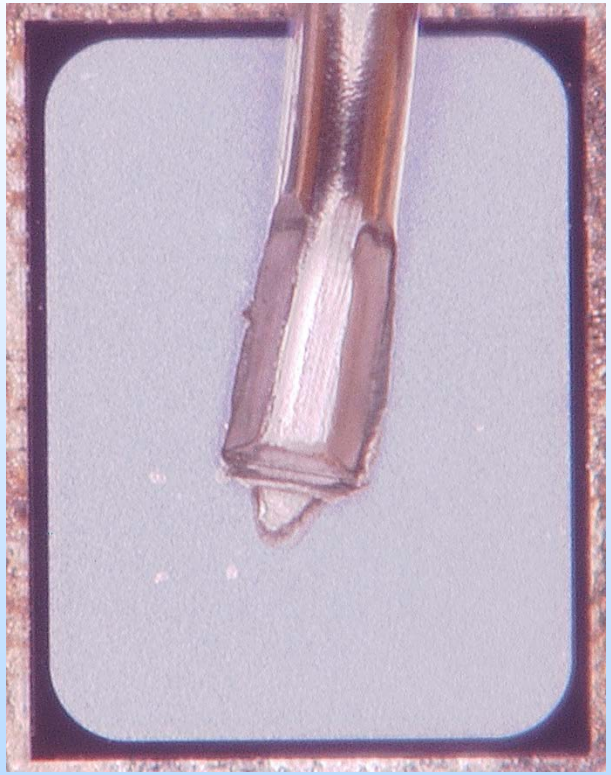
- Diode was examined using an IR camera and pictures were taken with a small voltage applied
  - Bright white spot just below the wirebond contact is the location of the failure
- Low-magnitude and high-magnitude optical images of the surface of the DUT did not show anything unusual at the location identified in the IR image



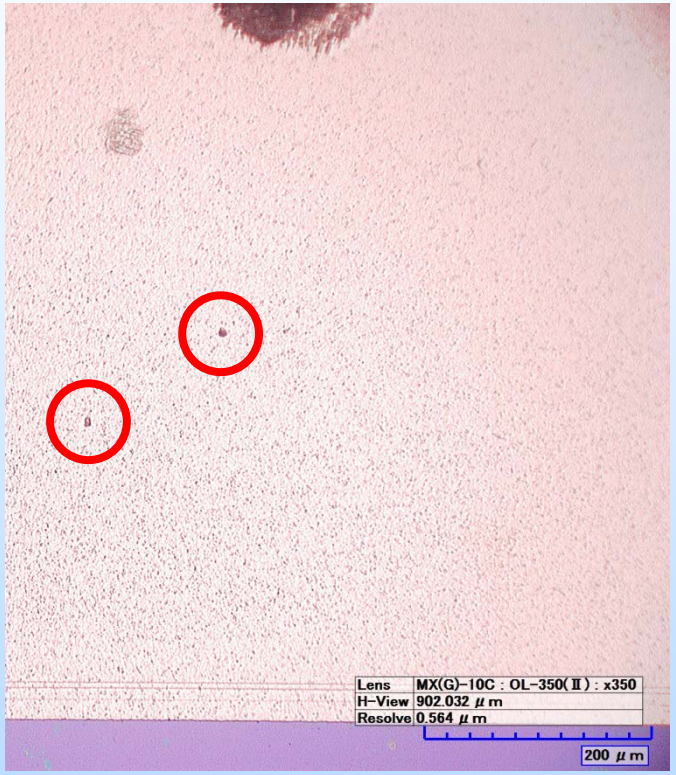
Catastrophic Failure

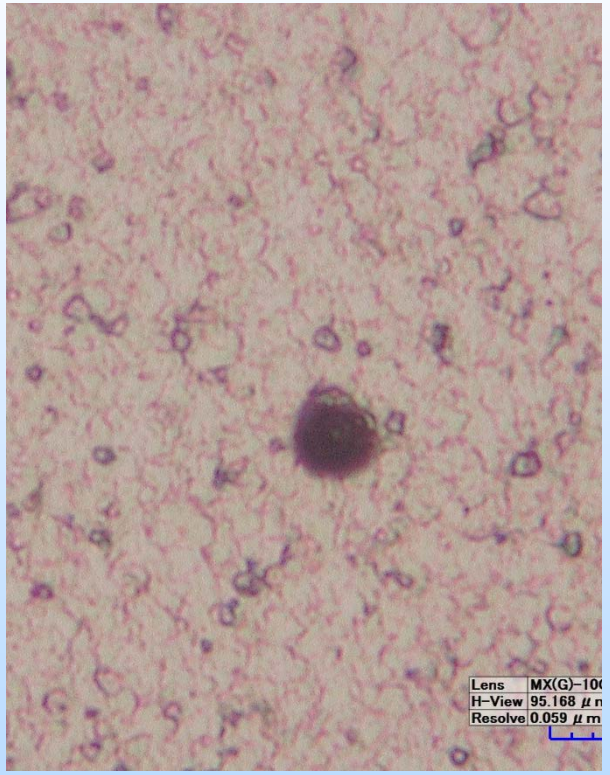
Optical Images of DUT

Low-Magnification



High-Magnification



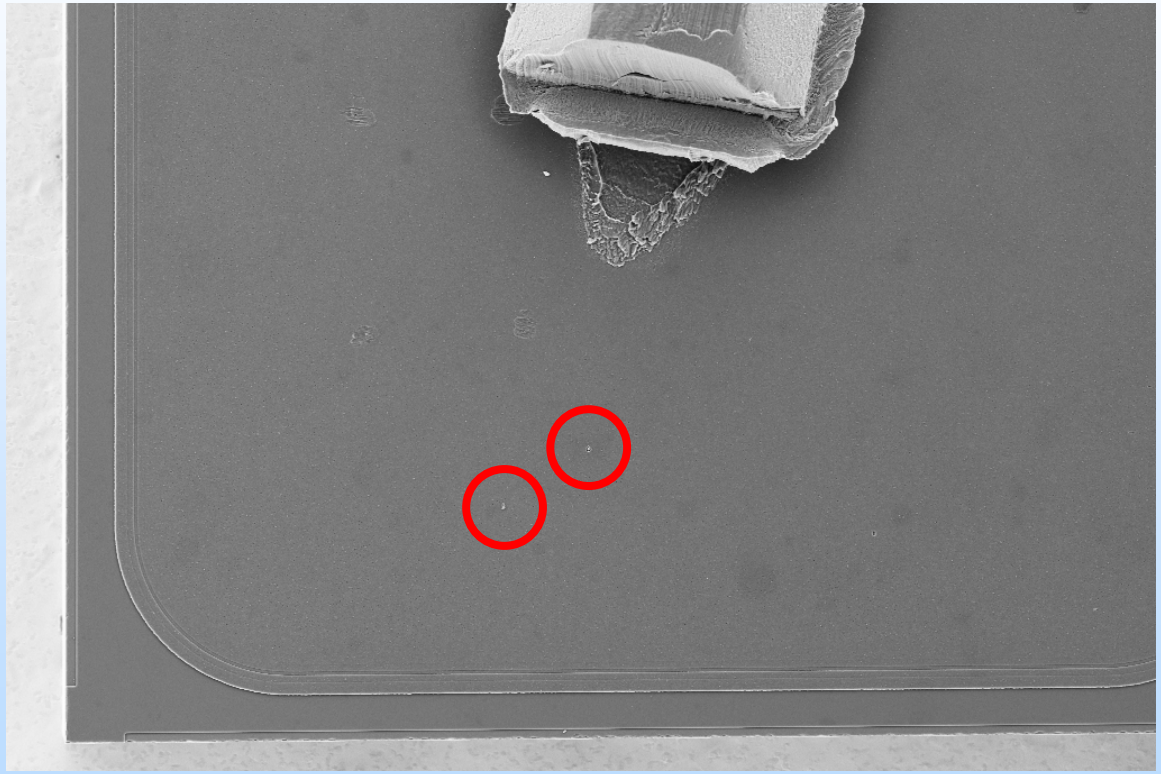


Unlike other part that experienced catastrophic failure, location is visible in high-magnification optical images

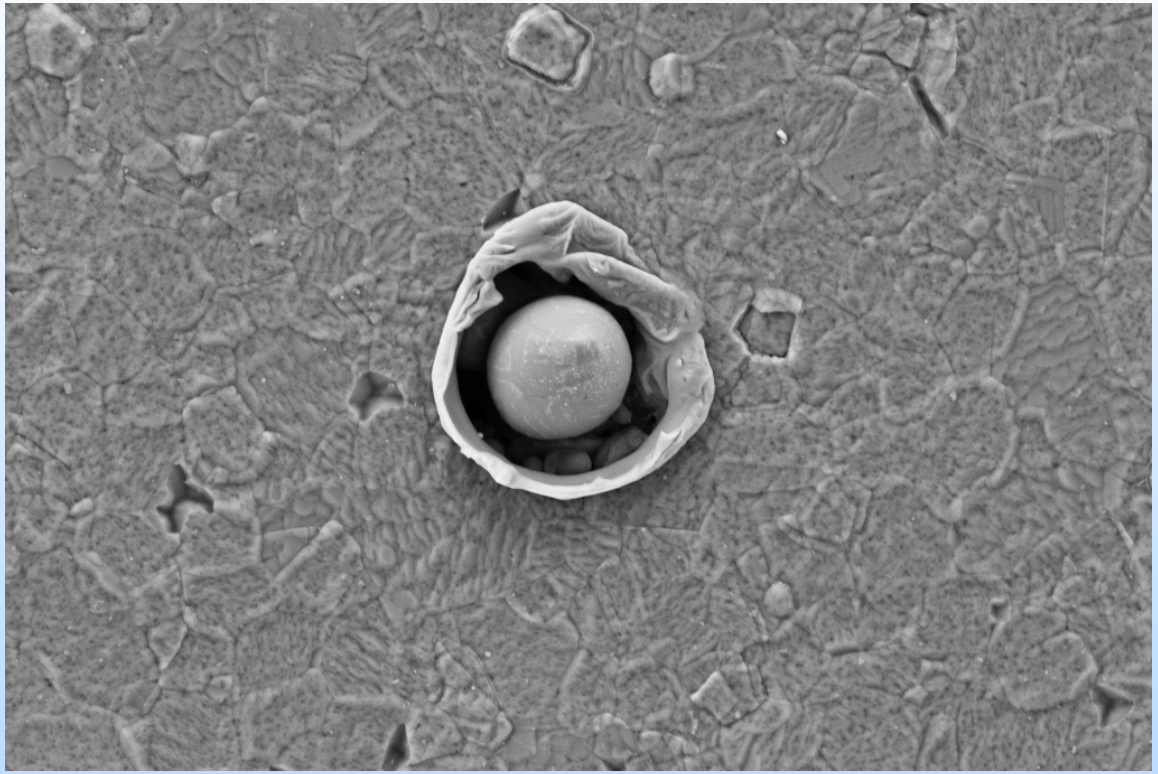
Catastrophic Failure

Surface SEMs of Failure Location

Low-Magnification SEM Image



Scanning Electron Microscope Image

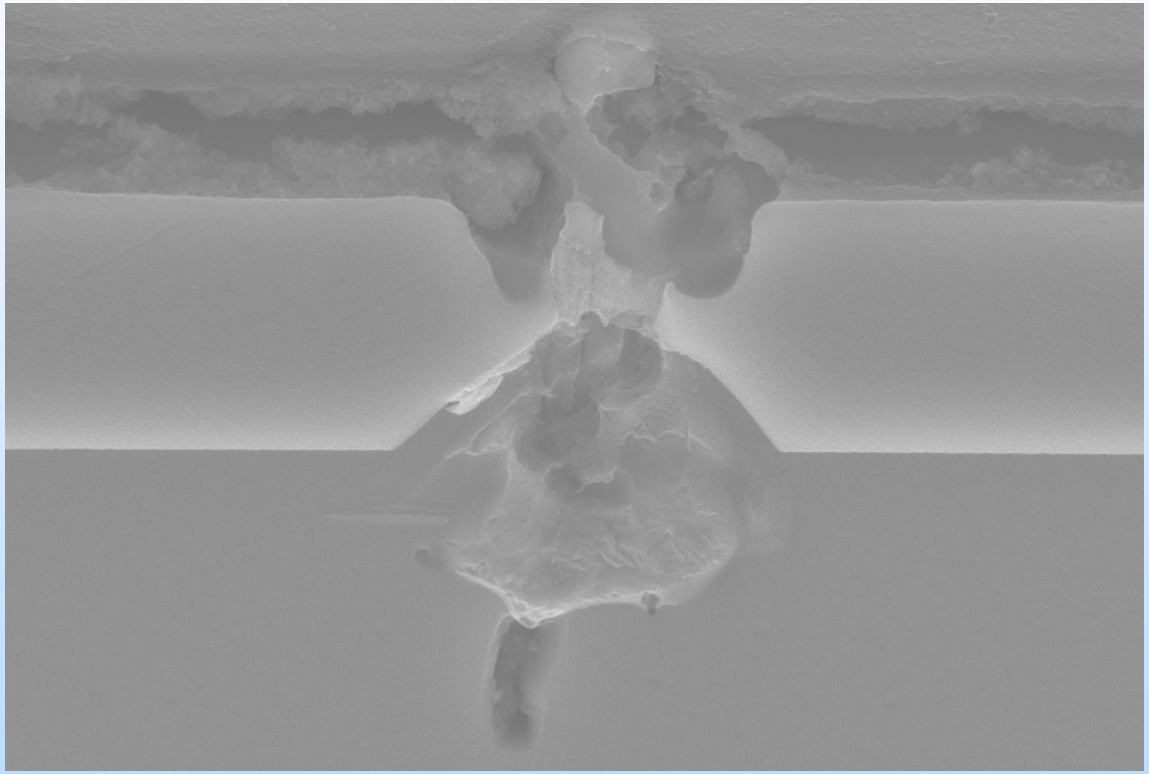


Catastrophic Failure

Cross-Section at Failure Location

High-Magnification Optical Image

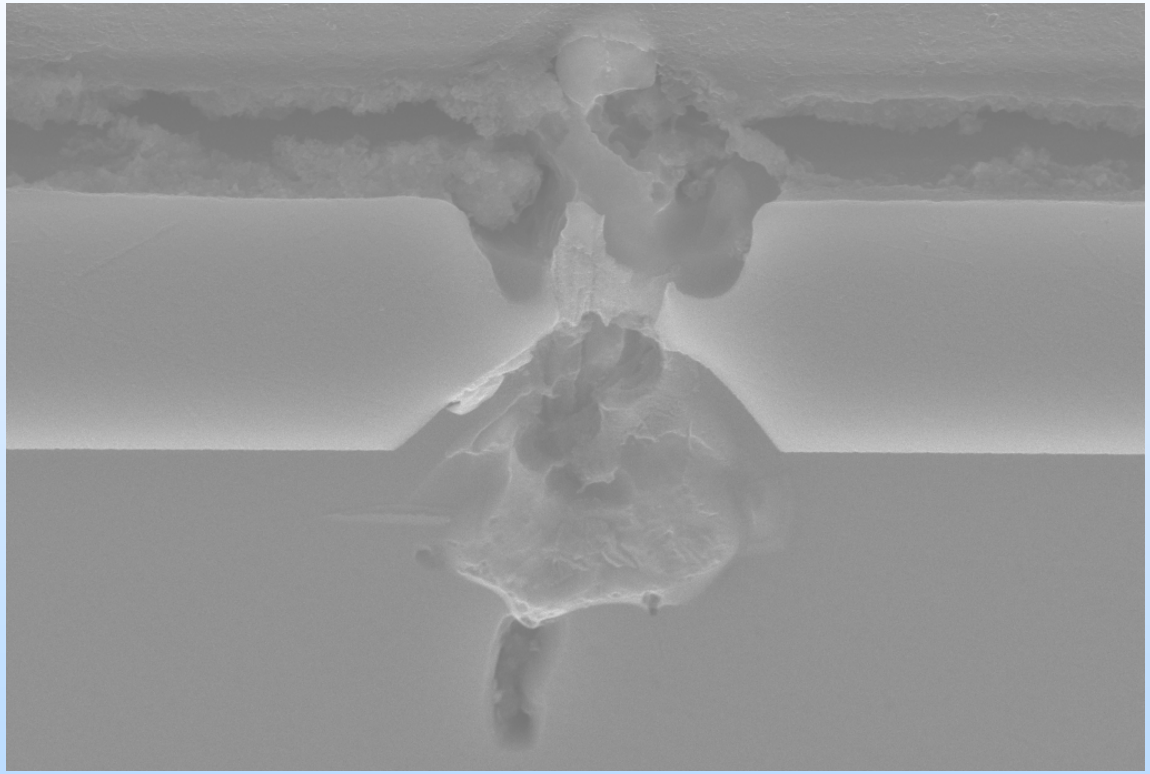
Scanning Electron Microscope Image



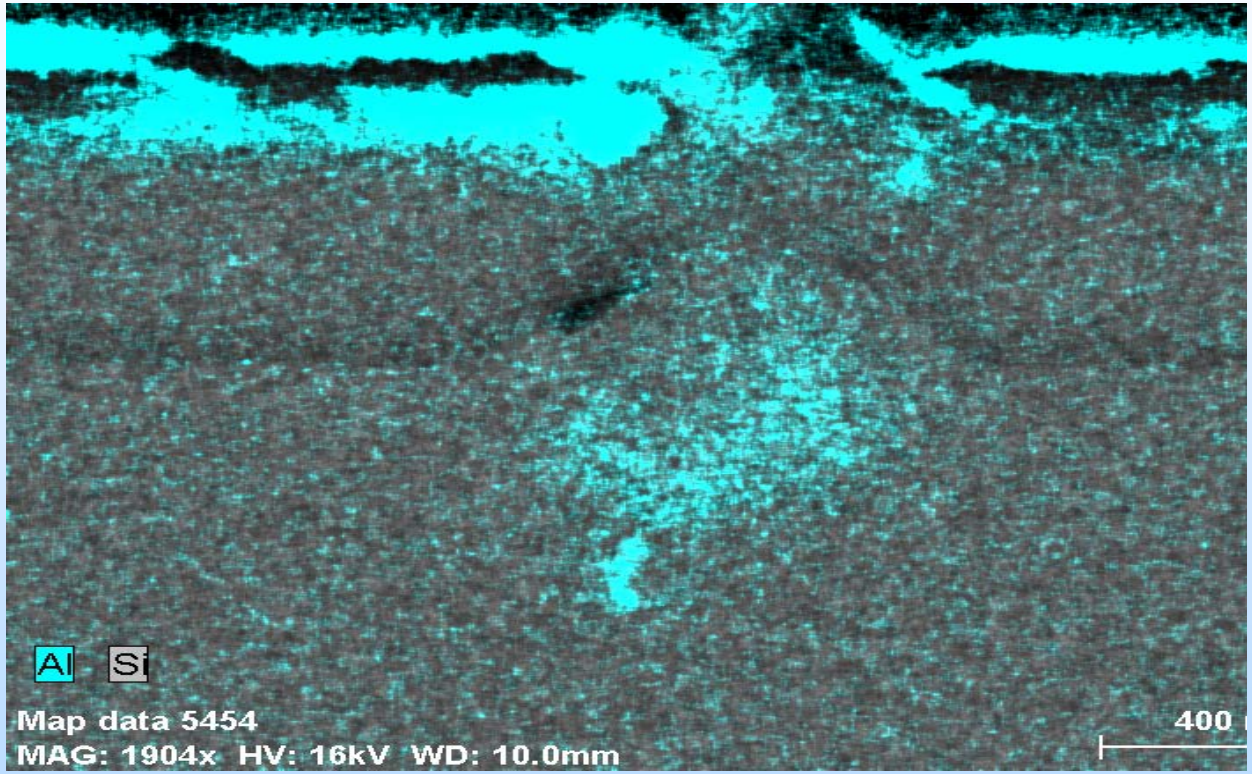
Catastrophic Failure

Energy Dispersive X-Ray Spectroscopy

SEM Cross-Section Image



Map of Al and Si



Metal has clearly displaced from Schottky junction into void formed from high current

Conclusions

Conclusions

- Only diodes with a Schottky junction appear to experience catastrophic failure under the conditions tested
- Degradation was observed in an RF switching diode and several Zener diodes
  - While all measured electrical parameters remained within specification after degradation was observed, the long-term reliability of these parts is unknown
- Degradation and failure mechanisms are not limited to power devices

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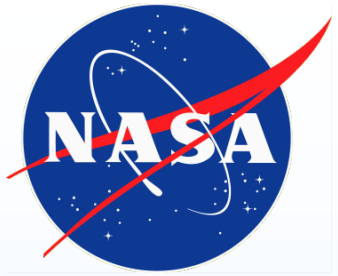
- Failure analysis shows clear failure locations in parts that experience catastrophic failure when examined with an IR camera
- Parts that experience degradation do not appear to have deep internal failure structures that are observable when cross-sectioned
- When the anode and cathode short in diodes due to destructive SEEs, Schottky metal displaces and creates the conducting path

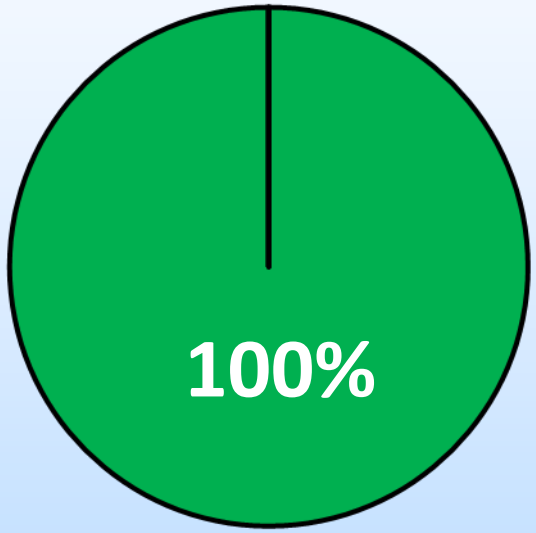


Backup Slides

Results – Avalanche Diode

- Only one avalanche diode type was tested
  - We were limited in our options due to packaging issues

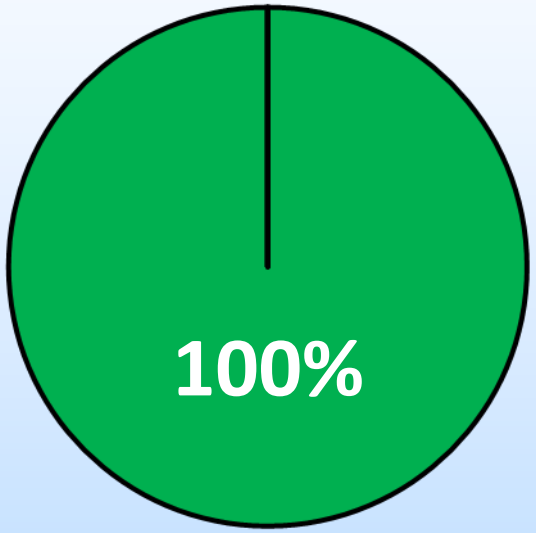
Manufacturer	Part Number	Reverse Voltage	Forward Current
NXP Semi	BAS29,215	90 V	200 mA



100% of Rated Reverse Voltage

Results – PiN Diodes

Manufacturer	Part Number	Reverse Voltage	Forward Current
NXP Semi	BAT18,215	35 V	100 mA
NXP Semi	BAP50-05,215	50 V	50 mA
Broadcom	HSMP-3810-TR1G	100 V	1 A
M/A-COM	MA4P7455CK-287T	100 V	150 mA
Infineon	BAR64-05 E6327	150 V	100 mA
NXP Semi	BAP64-05,215	175 V	100 mA
Skyworks	SMP1307-004LF	200 V	100 mA



100% of Rated Reverse Voltage

Diodes, Inc. BAS21-7-F Switching Diode

- Small changes in the reverse current were observed during the runs in which these parts were biased at the full-rated 200-V reverse voltage

- Small changes in the I_R-V_R and I_F-V_F plots were observed after the runs
  - How these changes effect the long-term reliability of the parts is unknown